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TECHNICAL REPORT ARLCD-TR-79019

DERIVATION OF THE KINEMATIC PROPERTIES  
OF THE PIN PALLET RUNAWAY ESCAPEMENT

C. W. JANOW  
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OCTOBER 1979



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND  
LARGE CALIBER  
WEAPON SYSTEMS LABORATORY  
DOVER, NEW JERSEY

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<p>The operation of the pin pallet runaway escapement has been characterized in terms of several kinematic properties, i.e., velocity ratio, torque transfer ratio, and efficiency. A computer program has been written which analyzes both the entrance and exit phases of the engagement cycle. The influence of changes in the operating center distance has also been investigated by appropriate computer runs. As a result of this study, an analytic tool for the evaluation of the performance of proposed pin pallet escapement designs or for the modification of existing mechanisms is now available.</p>		

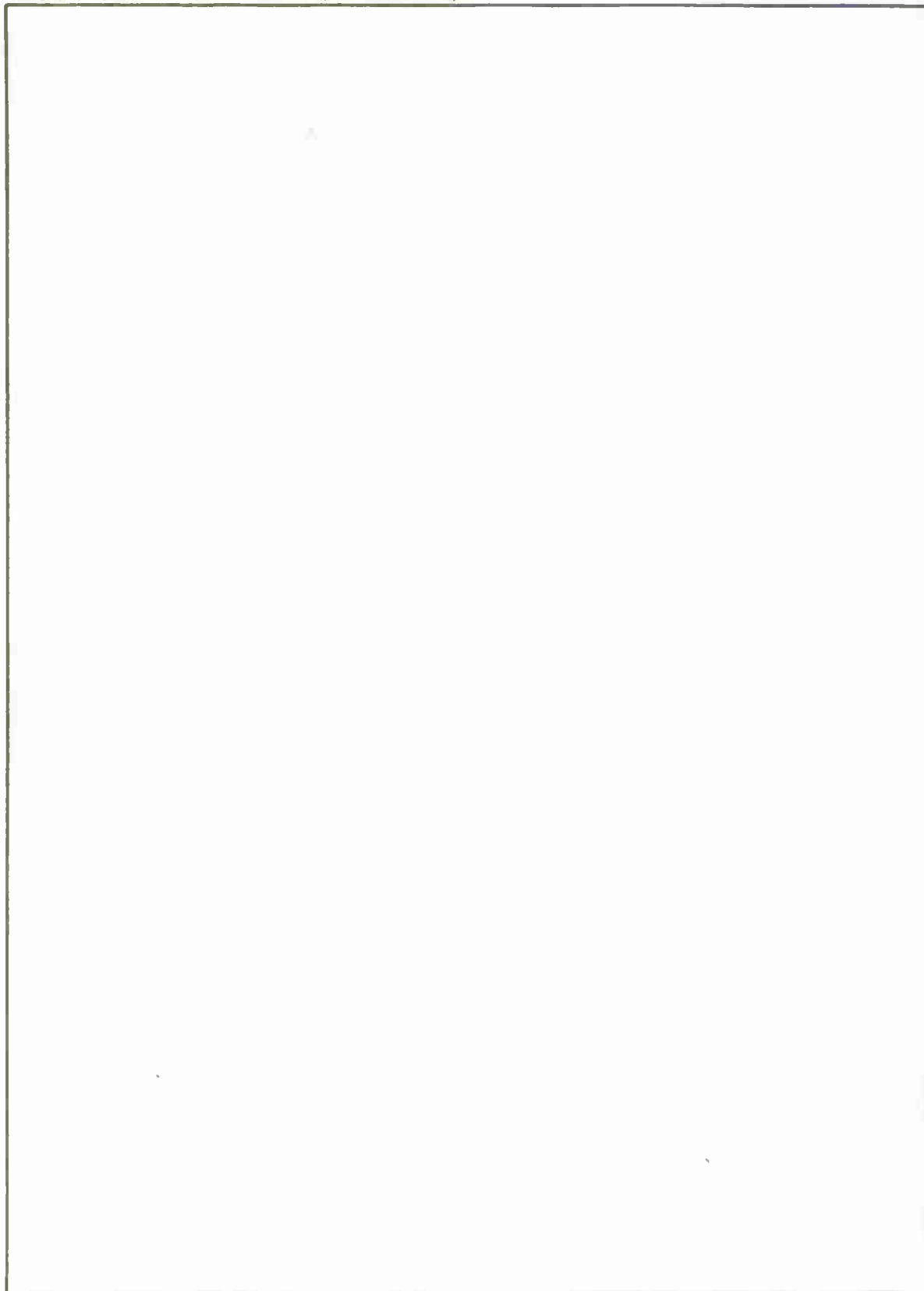
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## FOREWORD

This report is the first in a series of reports documenting analytical efforts undertaken as part of the Standard S&A Program. Other reports to follow will deal with the plate pallet, the involute gear mesh, and the clock tooth gear mesh, as well as the entire S&A mechanism.

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## INTRODUCTION

The pin pallet escapement is commonly employed in fuze safing and arming devices to provide a safe separation distance for arming. This report describes the results of an analytic investigation undertaken to characterize the performance of this type of escapement. The analysis is static in that it is based on the kinematics of the escapement and does not take into consideration the forces acting on the device. However, the analysis provides a useful tool for obtaining information to insure that the escapement will start, and that the motion during engagement of the components will be smooth and continuous.

## DESCRIPTION OF OPERATION OF PIN PALLET ESCAPEMENT

A schematic diagram of a typical pin pallet is presented in figure 1. As shown, this escapement consists of two elements. One of these is the pallet, which has two pins attached to it. These pins alternately make contact with the faces of the second element, the escape wheel. The escape wheel is usually connected by a step-up gear train to the element in the fuze system whose motion must be retarded.

The principle of operation of the pin pallet escapement is as follows: Torque is applied to the component to be retarded by the spin of the projectile for an artillery fuze, or by a spring or shell acceleration for other fuzes. This torque is transmitted through the gear train to the escape wheel. As a result of this, the escape wheel will start to rotate and cause the engaging pallet pin to slide up the face of the escape wheel tooth. After the pin has reached the vertex of the tooth, the pallet and escape wheel will move independently. This will continue until the second pallet pin collides with another escape wheel tooth.

The impact theoretically causes the motion of the escape wheel to be instantaneously halted. In actuality, the motion of the escape wheel is usually only slowed, but it is also possible for the escape wheel to momentarily reverse its direction of motion. Of course, whatever motion is experienced by the escape wheel is transmitted back to the element to be retarded through the gear train. In this manner, the required delay is achieved. The step-up gear train is utilized in order to increase the number of impacts between the pallet and escape wheel thereby increasing the number of times the motion of the escape wheel is interrupted.

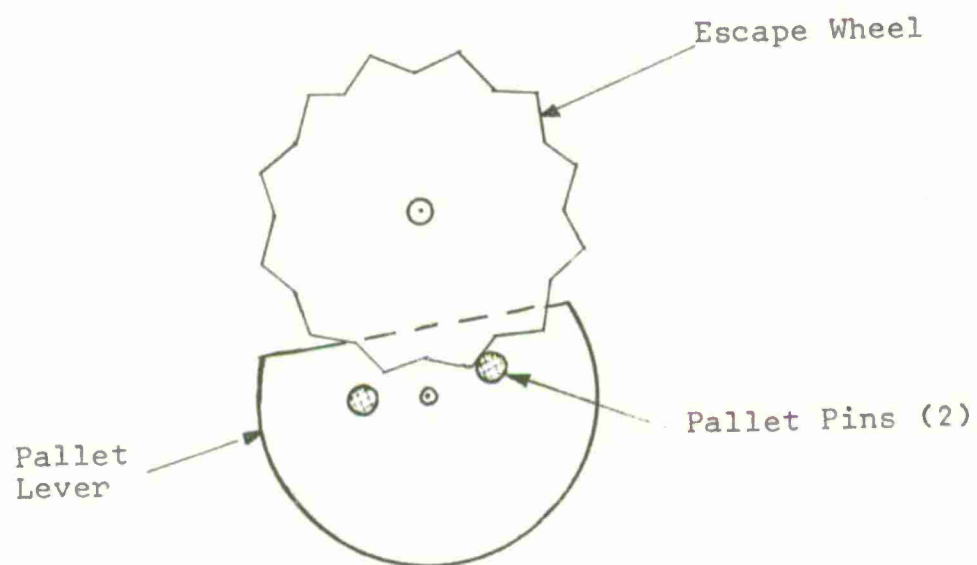


Figure 1. Pin pallet runaway escapement.

## ANALYSIS

This section describes the study conducted to characterize the performance of the pin pallet escapement, during the engagement of the pallet and the escape wheel, in terms of its kinematic properties. These include the instantaneous velocity ratio, efficiency and the moment arms of the input and output forces. These parameters furnish the information necessary to determine if an escapement will start and if motion during engagement will be smooth and continuous. Some of the work is excerpted from appendices A, B, and G of reference 1 and is reproduced here, where necessary, for completeness.

### Nomenclature

Figure 2 shows the kinematic relationship of the escape wheel and pallet when they are in contact. In this configuration the upper pallet pin (usually referred to as the entrance pallet pin) is being driven by the escape wheel tooth. The following nomenclature is used throughout the remainder of this report:

- $\phi$  = Escape wheel angle. Defined by the line from the escape wheel pivot  $O_s$  to the tip of the contacting tooth, and the line connecting  $O_s$  to the pallet pivot  $O_p$ .
- $\psi$  = Pallet angle. Defined by the line from  $O_p$  to the active pin center and the centerline.
- $a$  = Distance between pivot points  $O_p$  and  $O_s$
- $b$  = Escape wheel outer radius
- $c$  = Pallet pin radius, to center of pallet pin
- $r$  = Pallet pin radius
- $\alpha$  = Escape wheel tooth half angle
- $g$  = Distance from the contact point to the tip of the escape wheel tooth.

The identical nomenclature will be used for the lower pallet pin (usually referred to as the exit pallet pin).

## Kinematics

### Determination of $\psi$ and $g$

Referring to figure 2, the unit vectors  $\bar{n}_t$  and  $\bar{n}_n$  are defined along and perpendicular to the contact surface of the escape wheel tooth in the indicated direction and are given by:

$$\bar{n}_t = \cos (\varphi - \alpha) \bar{i} + \sin (\varphi - \alpha) \bar{j} \quad (1)$$

$$\bar{n}_n = -\sin (\varphi - \alpha) \bar{i} + \cos (\varphi - \alpha) \bar{j} \quad (2)$$

The unit vectors  $\bar{n}_b$  along the line joining the escape wheel center with the tooth tip, and  $\bar{n}_c$  along the line connecting the pallet pivot and the pallet pin center, are given by:

$$\bar{n}_b = \cos \varphi \bar{i} + \sin \varphi \bar{j} \quad (3)$$

$$\bar{n}_c = \cos \psi \bar{i} + \sin \psi \bar{j} \quad (4)$$

The loop closure equation of this mechanism can be used to determine the pallet angle  $\psi$  and the distance  $g$  with respect to the tip of the escape wheel as functions of the angle  $\varphi$ .

$$0 = b(\cos \varphi \bar{i} + \sin \varphi \bar{j}) + g[\cos(\varphi - \alpha) \bar{i} + \sin(\varphi - \alpha) \bar{j}] \\ + r[-\sin(\varphi - \alpha) \bar{i} + \cos(\varphi - \alpha) \bar{j}] - c(\cos \psi \bar{i} + \sin \psi \bar{j}) + a \bar{i}$$

Rewriting the above in component form:

$$b \cos \varphi + g \cos (\varphi - \alpha) - r \sin (\varphi - \alpha) - c \cos \psi + a = 0 \quad (5)$$

$$b \sin \varphi + g \sin (\varphi - \alpha) + r \cos (\varphi - \alpha) - c \sin \psi = 0 \quad (6)$$

The angle  $\psi$  is then obtained from:

$$\sin \psi = \frac{[b \sin \varphi + g \sin (\varphi - \alpha) + r \cos (\varphi - \alpha)]}{c} \quad (7)$$

and

$$\cos \psi = \frac{[c^2 - (b \sin \varphi + g \sin (\varphi - \alpha) + r \cos (\varphi - \alpha))^2]^{1/2}}{c} \quad (8)$$

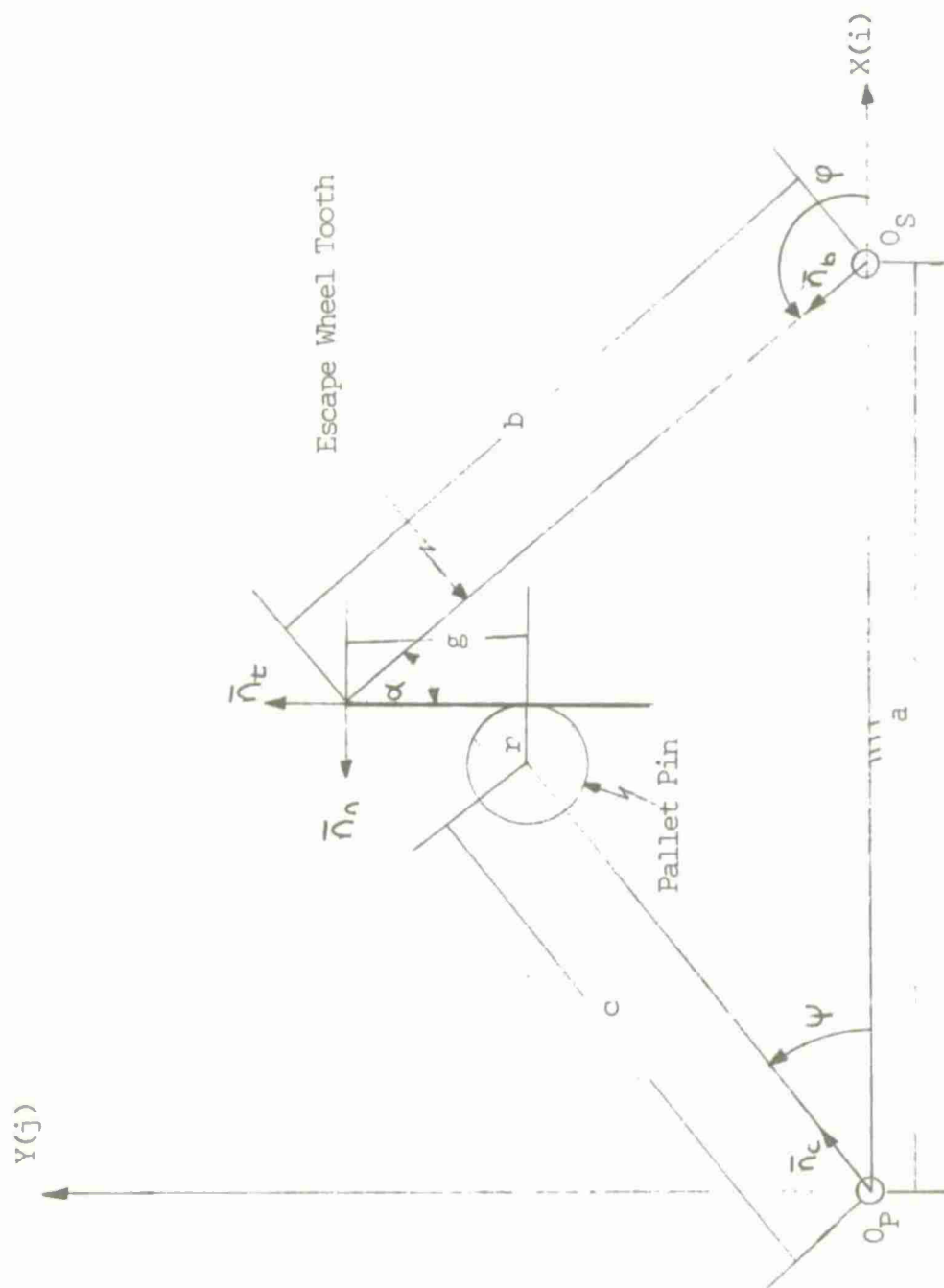


Figure 2. Kinematic relationship coupled motion.



Substituting equation (8) into equation (5) and squaring both sides furnishes

$$[b\cos\phi + g\cos(\phi - \alpha) - r\sin(\phi - \alpha) + a]^2 = c^2 - [b\sin\phi + g\sin(\phi - \alpha) + r\cos(\phi - \alpha)]^2$$

Rearranging the above yields:

$$g^2 + g[2b\cos\alpha + 2a\cos(\phi - \alpha)] = c^2 - b^2 - a^2 - r^2 - 2br\sin\alpha - 2bacos\phi + 2rasin(\phi - \alpha)$$

or

$$g^2 + 2[b\cos\alpha + a\cos(\phi - \alpha)]g + b^2 + a^2 + r^2 - c^2 + 2br\sin\alpha + 2bacos\phi - 2rasin(\phi - \alpha) = 0 \quad (9)$$

The solution to (9) is given by:

$$g_{1,2} = \frac{-H \pm \sqrt{H^2 - 4K}}{2} \quad (10)$$

where

$$H = 2[b\cos\alpha + a\cos(\phi - \alpha)] \quad (11)$$

$$K = b^2 + a^2 + r^2 - c^2 + 2br\sin\alpha + 2bacos\phi - 2rasin(\phi - \alpha) \quad (12)$$

The correct value of  $g$  must be the one with the smallest absolute value. Thus,

$$\text{if } |g_1| < |g_2| \quad g = g_1$$

$$\text{otherwise, } g = g_2$$

Determination of maximum value of  $g$  and corresponding  $\phi$

At the starting position for either entrance or exit engagement, the pallet pin is located deep in the root between two escape wheel teeth. This location corresponds to the maximum value of  $g$ . This value will now be determined with the help of figure 3, which shows the pallet pin at position  $g = g_{\max}$ .

From  $\Delta OST$  the following relationship is obtained:

$$\angle OST = \pi - \alpha - \delta/2 \quad (13)$$

where  $\delta = 360/N$

$N$  = number of teeth of the escape wheel.

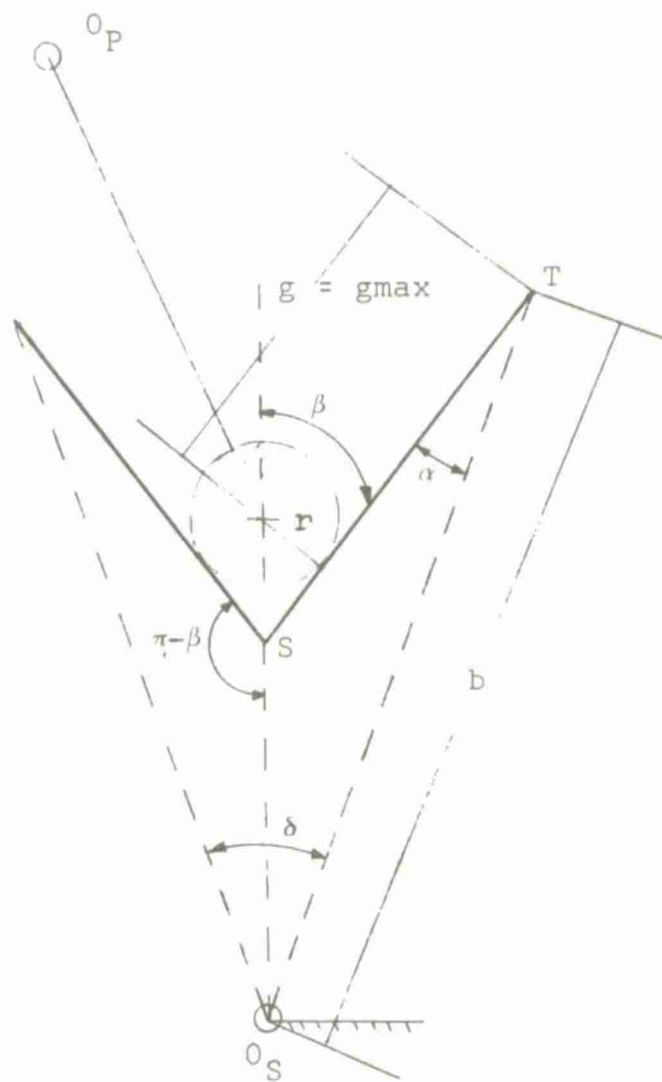


Figure 3. Pallet pin in starting position.

Since  $\beta = \alpha + \frac{\delta}{2}$  equation (13) becomes:

$$\angle O_s ST = \pi - \beta \quad (14)$$

The distance  $\overline{ST}$  of  $\triangle O_s ST$  is determined with the help of the sine law:

$$\overline{ST} = \frac{b \sin(\delta/2)}{\sin(\pi - \beta)} \quad (15)$$

Finally,  $g_{\max}$  is given by:

$$g_{\max} = -\left(ST - \frac{r}{\tan \beta}\right) \quad (16)$$

Note that in order to conform to the  $\overline{n}_t - \overline{n}_n$  coordinate system, in which  $g_{\max}$  is a negative quantity, a minus sign has been assigned to the above expression.

The angle  $\varphi = \varphi_M$  which corresponds to the orientation of the escape wheel when  $g = g_{\max}$  is determined from equation (9). With the help of the trigonometric identities for  $\cos(\varphi_M - \alpha)$  and  $\sin(\varphi_M - \alpha)$  and expressing  $\sin \varphi_M$  and  $\cos \varphi_M$  in terms of  $\tan(\varphi_M/2)$ , equation (9) be arranged as:

$$L \sin \varphi_M + M \cos \varphi_M + N = 0 \quad (17)$$

where

$$L = 2a [g_{\max} \cdot \sin \alpha - r \cos \alpha]$$

$$M = 2a [b + g_{\max} \cdot \cos \alpha + r \sin \alpha]$$

$$N = g_{\max}^2 + b^2 + a^2 + r^2 - c^2 + 2b(g_{\max} \cdot \cos \alpha + r \sin \alpha)$$

or

$$\frac{2L \tan(\varphi_M/2)}{1 + \tan^2(\varphi_M/2)} + \frac{M - M \tan^2(\varphi_M/2)}{1 + \tan^2(\varphi_M/2)} + N = 0$$

or

$$(N - M) \tan^2(\varphi_M/2) + 2L \tan(\varphi_M/2) + M + N = 0$$

therefore;

$$\varphi_{M1,2} = 2 \tan^{-1} \left[ \frac{-L \pm \sqrt{L^2 - N^2 + M^2}}{N - M} \right] \quad (18)$$

The two solutions correspond to entrance and exit engagement starting positions.

Determination of  $\phi$  for  $g = 0$

The angle  $\varphi = \varphi_0$ , which corresponds to the orientation of the escape wheel when the pallet pin leaves the contacting tooth, may also be obtained from equation (9), by letting  $g = 0$ :

$$0 = b^2 + a^2 + r^2 - c^2 + 2br \sin \alpha + 2ba \cos \varphi_0 - 2ra \sin(\varphi_0 - \alpha) \quad (19)$$

With similar trigonometric substitutions as those made above, equation (19) may be written as:

$$L_0 \sin \varphi_0 + M_0 \cos \varphi_0 + N_0 = 0 \quad (20)$$

where:

$$L_0 = -2r \cos \alpha$$

$$M_0 = 2a(r \sin \alpha + b)$$

$$N_0 = b^2 + a^2 + r^2 - c^2 + 2br \sin \alpha$$

or

$$\frac{2L_0 \tan(\varphi_0/2)}{1 + \tan^2(\varphi_0/2)} + \frac{M_0 - M_0 \tan^2(\varphi_0/2)}{1 + \tan^2(\varphi_0/2)} + N_0 = 0$$

which can be further reduced to:

$$(N_0 - M_0) \tan^2(\varphi_0/2) + 2L_0 \tan(\varphi_0/2) + M_0 + N_0 = 0 \quad (21)$$

the solution of which is

$$\varphi_{0,2} = 2 \tan^{-1} \left[ \frac{-L_0 \pm \sqrt{L_0^2 - N_0^2 + M_0^2}}{N_0 - M_0} \right] \quad (22)$$

As before the two solutions correspond to the entrance and exit engagement loss of contact positions.

## Kinematic Properties

### Moment Arms

Having obtained both the starting positions and the last positions of coupled motion of the escapement the various kinematic properties of interest may be determined for any position in either entrance or exit engagement.

Figure 4 shows the pin pallet and escape wheel in coupled motion during entrance engagement. In this phase, both the escape wheel and the pallet are rotating in the same direction. The forces between the escape wheel and the pallet pin are represented by the normal force  $\bar{P}$  and the friction force  $\mu\bar{P}$  acting in the indicated directions.

The moment arms of the forces about the escape wheel center are represented by  $A_1$  and  $B_1$  and are given by:

$$A_1 = b \cos \alpha + g \quad (23)$$

$$B_1 = b \sin \alpha \quad (24)$$

The line  $00'$  represents the line of action of the contacting force  $P$  when friction is not taken into account. The introduction of the friction force at the point of contact causes the line of action of the resultant force to be along line  $00''$ , which makes an angle  $\xi$  with line  $00'$ . This angle is given by:

$$\xi = \tan^{-1} \mu$$

The moment arm  $A_w$  of the resultant force may be determined in the following manner. From triangle  $0_s00''$  it can be seen that

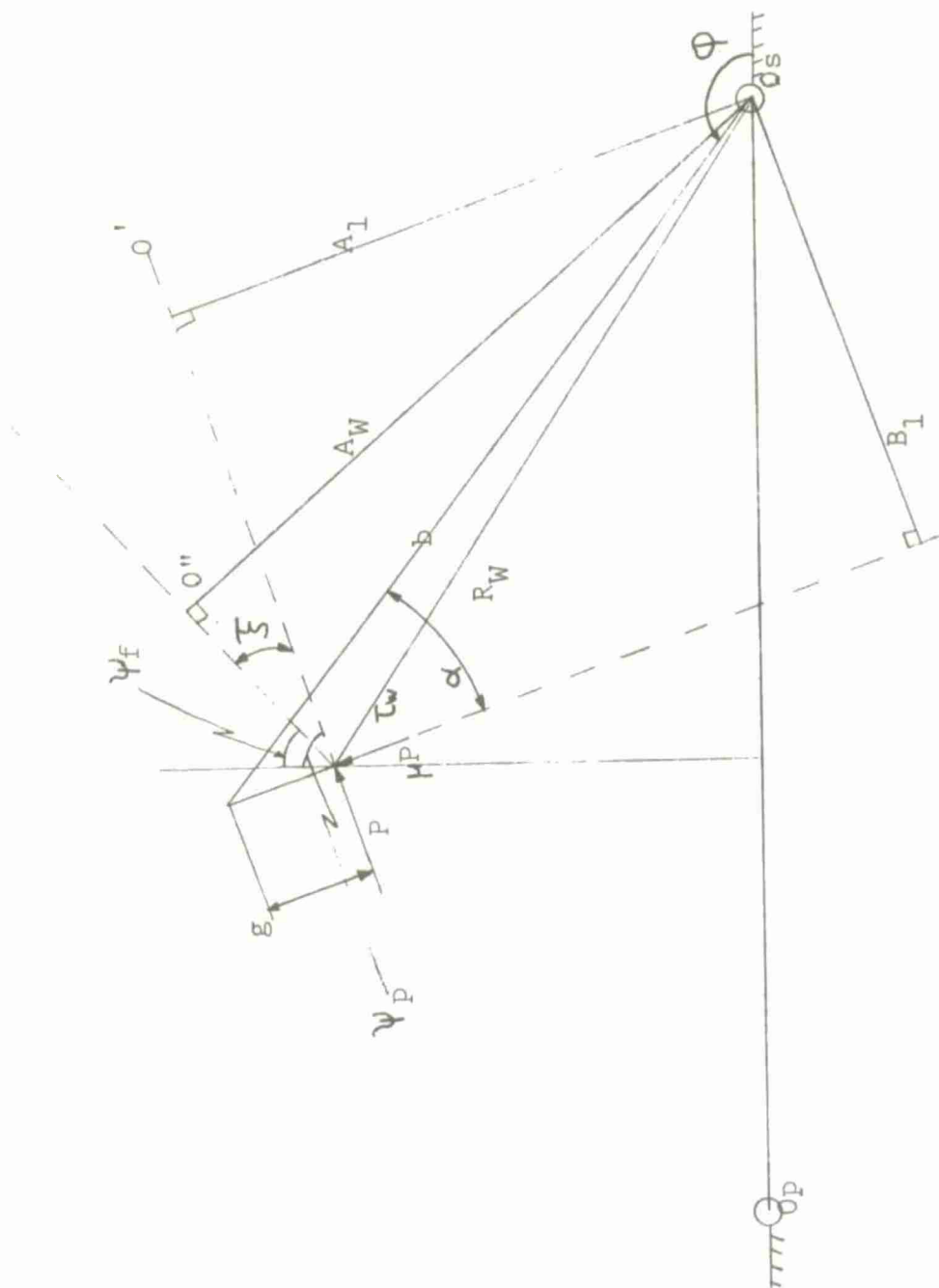


Figure 4. Escape wheel - entrance engagement.



$$R_w = \sqrt{A_1^2 + B_1^2}$$

$$\angle O_1 O_S O = \tau_w = \tan^{-1} \frac{B_1}{A_1}$$

With  $\angle O_1 O_S O'' = \xi$ ;  $\angle O_1'' O_S O$  becomes:  $\angle O_1'' O_S O = \tau_w - \xi$

and

$$A_w = R_w \cos(\tau_w - \xi) \quad (25)$$

In a manner similar to that for gears, the pressure angle may be defined as the angle that the line of action of the contact force makes with a line which is normal to the centerline at the contacting point. From figure 4, it can be seen that the pressure angle  $\psi_f$  can be written as:

$$\psi_f = \pi + \alpha - \varphi \quad (26)$$

When friction is considered, the pressure angle, corrected for friction is given by:

$$\psi_f = \psi_p - \xi \quad (27)$$

Before the kinematics of the pallet may be investigated, expressions for the moment arms of the normal and friction forces acting on the pallet pins must be derived. This will be accomplished with the help of figure 5. This figure shows the moment arms  $D_1$  for the normal force, and  $C_1$  for the friction force, acting on the pallet pin.

The following loop equation is used to obtain  $C_1$  and  $D_1$  (see fig. 5):

$$C_1 \bar{n}_c - r \bar{n}_n - D_1 \bar{n}_t + C_1 \bar{n}_n = 0 \quad (28)$$

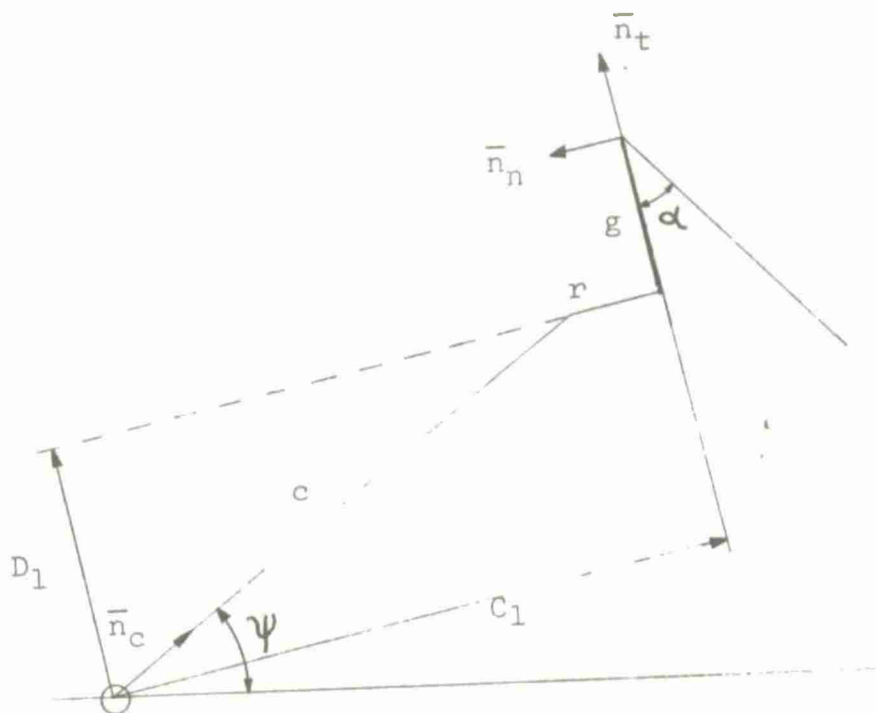


Figure 5. Moment arms about pallet pivot.

Upon substitution of the following

$$\bar{n}_t = \cos(\varphi-\alpha)\bar{i} + \sin(\varphi-\alpha)\bar{j}$$

$$\bar{n}_n = -\sin(\varphi-\alpha)\bar{i} + \cos(\varphi-\alpha)\bar{j}$$

$$\bar{n}_c = \cos\psi\bar{i} + \sin\psi\bar{j}$$

equation (28) becomes:

$$\begin{aligned} C\cos\psi\bar{i} + C\sin\psi\bar{j} + r\sin(\varphi-\alpha)\bar{i} - r\cos(\varphi-\alpha)\bar{j} - D_1\cos(\varphi-\alpha)\bar{i} \quad (29) \\ -D_1\sin(\varphi-\alpha)\bar{j} + C_1\cos(\varphi-\alpha)\bar{j} - C_1\sin(\varphi-\alpha)\bar{i} = 0 \end{aligned}$$

or, separating into components:

$$C\cos\psi + r\sin(\varphi-\alpha) - D_1\cos(\varphi-\alpha) - C_1\sin(\varphi-\alpha) = 0$$

$$C\sin\psi - r\cos(\varphi-\alpha) - D_1\sin(\varphi-\alpha) + C_1\cos(\varphi-\alpha) = 0$$

Multiplying the first equation by  $\cos(\varphi-\alpha)$  and the second equation by  $\sin(\varphi-\alpha)$ , and adding, leads to:

$$C[\cos\psi\cos(\varphi-\alpha) + \sin\psi\sin(\varphi-\alpha)] - D_1 = 0$$

or

$$D_1 = C\cos(\varphi-\alpha-\psi) \quad (30)$$

Similarly, multiplying the first equation by  $\sin(\varphi-\alpha)$  and the second by  $\cos(\varphi-\alpha)$  and adding, yields:

$$C[\sin(\varphi-\alpha)\cos\psi - \cos(\varphi-\alpha)\sin\psi] + r - C_1 = 0$$

or

$$C_1 = r + C\sin(\varphi-\alpha-\psi) \quad (31)$$

Figure 6 depicts the pallet pin in entrance engagement with the escape wheel. The contact force  $P$  on the pin, and the associated friction force  $\mu P$ , ( $\mu$  represents the coefficient of friction) act in the directions shown, which are opposite to the directions of the forces applied on the escape wheel tooth.



As before, the introduction of the friction force causes the line of action of the contact force,  $00'$ , to be displaced an angle  $\xi$  to line  $00''$ , where

$$\xi = \tan^{-1} \mu$$

Letting

$$\angle 0'00_p = \tau p_1$$

where

$$\tau p_1 = \tan^{-1} \frac{D_1}{C_1} \quad (32)$$

and

$$\angle 0''00'' = \xi$$

then:

$$\angle 0''00_p = \tau p_1 - \xi$$

$$\text{With } R_p = \sqrt{C_1^2 + D_1^2} \quad (33)$$

the moment arm for the resultant force is given by:

$$A_p = R_p \sin(\tau p_1 - \xi) \quad (34)$$

#### Angular Velocity Ratio

The instantaneous angular velocity ratio, which is obtained by taking the ratio of the (uncorrected) moment arms of the contact force about the escape wheel and pallet pivots, becomes:

$$N = \frac{A_1}{D_1} \quad (35)$$

#### Torque Transfer Ratio

The ratio of the friction corrected moment arms is defined as the instantaneous torque transfer ratio, which is given by:

$$N_f = \frac{A_w}{A_p} \quad (36)$$

Note that in the absence of friction, this expression is identical to equation (35).

### Torque Transmission Efficiency

Finally, the efficiency  $E$  of torque transmission may be defined as the ratio of the torque transmitted to the pallet when friction is present to the torque transmitted in the absence of friction, i.e.,

$$E = \frac{A_p}{A_w} \bigg/ \frac{D_1}{A_1} = \frac{N}{N_f} \quad (37)$$

Upon making the appropriate substitutions, the above equation may be written as:

$$E = \frac{1 - \mu \left( \frac{C_1}{D_1} \right)}{1 + \mu \left( \frac{B_1}{A_1} \right)} \quad (38)$$

The quantity is a measure of the amount of the available torque actually transmitted to the pallet.

A similar analysis to the one described above is performed for positions in exit engagement. In this phase, the direction of rotation of the pallet is opposite to that of the escape wheel.

Figure 7 shows the forces acting on the escape wheel in exit engagement. Proceeding in a manner similar to that used in the analysis of entrance engagement, the following relationships are obtained:

$$R_w = \sqrt{B_1^2 + A_1^2} \quad (39)$$

$$\tau_w = \tan^{-1} \frac{A_1}{B_1} \quad (40)$$

$$\angle 0'00'' = \xi$$

$$\angle 0'00' = \tau_w$$



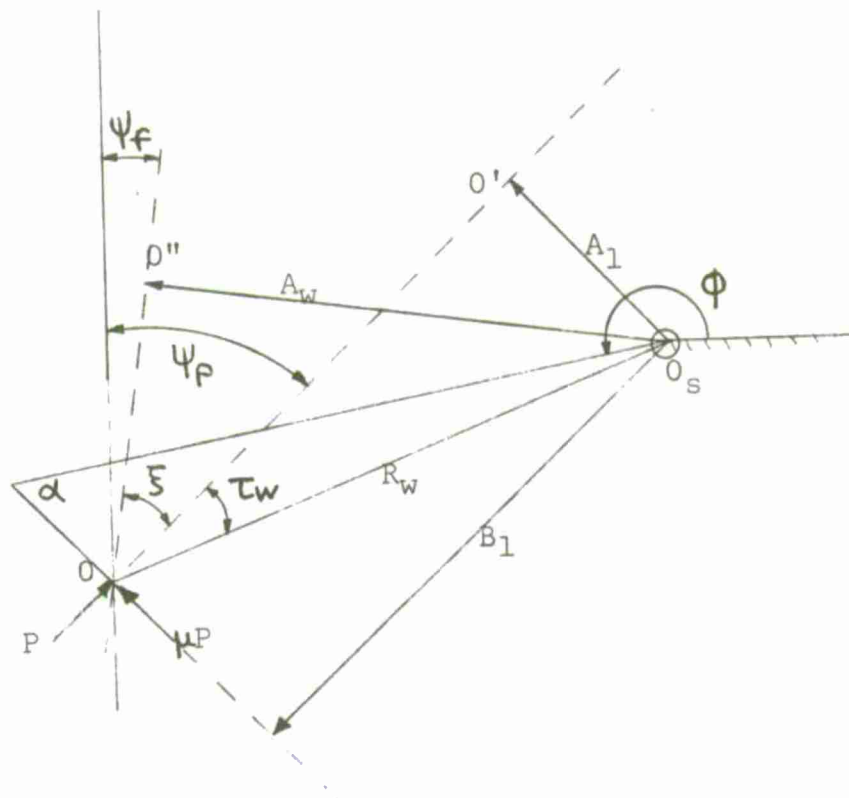


Figure 7. Escape wheel - exit engagement.

therefore;

$$\angle 0_s 00'' = \tau_w + \xi \quad (41)$$

and

$$A_w = R_w \sin(\tau_w + \xi)$$

The pressure angle is given by:

$$\psi_p = \pi + \alpha - \phi \quad (42)$$

and the friction corrected pressure angle becomes

$$\psi_f = \psi_p - \xi \quad (43)$$

In analyzing the pallet in exit engagement, it was discovered that two different modes of contact between the pallet pin and the escape wheel tooth exist. The first, which is illustrated in figure 8, occurs when the line of action of the friction force lies below the pallet pivot. In the second mode, illustrated in figure 9, the line of action of the friction force lies above the pallet pivot. Whether contact will be of the first or second mode depends solely on the geometry of the mechanism and on the operating center distance.

Mode one contact will be analyzed first. Following the same procedure employed in the analysis of the pallet in the entrance phase, the friction corrected moment arm and angle  $\tau_{p2}$  become (fig. 8):

$$R_p = \sqrt{C_1^2 + D_1^2} \quad (44)$$

$$\tau_{p2} = 180^\circ - \tan^{-1} \left( \frac{D_1}{C_1} \right) \quad (45)$$

The contact force  $P$  exerted on the pin, acts along the line of action  $OL$ . When the friction force  $\mu P$  is introduced, the line of action  $OL$  is rotated through  $\xi$  to a new position  $00''$ . Thus:

$$\angle 0'' 0_p L = \xi = \tan^{-1} \mu$$

$$\angle L 0_p 0 = \tau_{p2} - 90^\circ$$

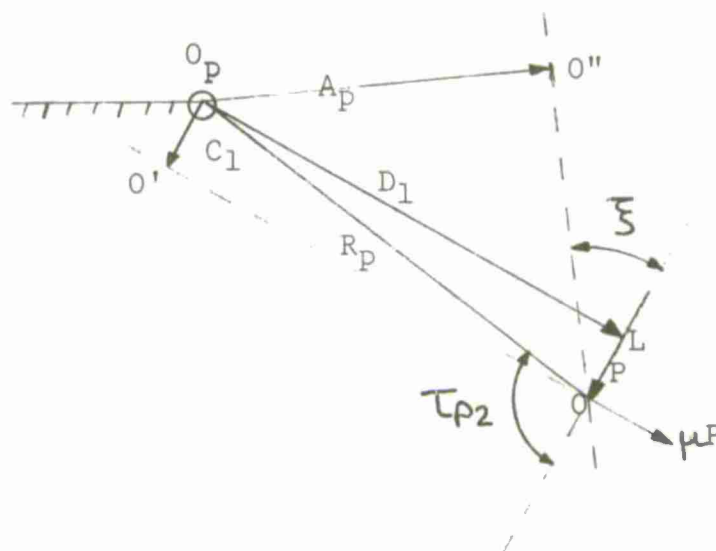


Figure 8. Pallet - exit engagement (mode 1)



therefore,

$$\alpha_{p0}'' = \tau_{p2} - 90^\circ + \xi$$

and

$$A_p = R_p \cos(\tau_{p2} - 90^\circ + \xi)$$

or,

$$A_p = R_p \sin(\tau_{p2} + \xi) \quad (46)$$

With equations (35) - (37) an expression for the efficiency of torque transmission for exit engagement with mode 1 contact may be obtained:

$$E = \frac{1 - \mu \left( \frac{C_1}{D_1} \right)}{1 + \mu \left( \frac{B_1}{A_1} \right)} \quad (47)$$

Note that this equation is identical to equation (38).

For mode 2 contact the following relationships occur (fig. 9):

$$R_p = \sqrt{C_1^2 + D_1^2} \quad (48a)$$

$$\alpha_{p0}'' = \tau_{p3} = \tan^{-1} \frac{C_1}{D_1} \quad (48b)$$

$$\alpha_{p0}'' = 90^\circ - \xi \quad (48c)$$

therefore:

$$\alpha_{p0}'' = \tau_{p3} + 90^\circ - \xi \quad (49)$$

and

$$A_p = R_p \sin(\tau_{p3} + 90^\circ - \xi)$$

or

$$A_p = R_p \cos(\tau_{p3} - \xi) \quad (50)$$

Finally, with equations (35) - (37) the efficiency for mode 2 contact becomes:

$$E = \frac{1 + \mu \left( \frac{C_1}{D_1} \right)}{1 + \mu \left( \frac{B_1}{A_1} \right)} \quad (51)$$

## DESCRIPTION OF COMPUTER PROGRAM

A listing of the FORTRAN computer program developed to perform this analysis is presented in appendix A. The program places the escapement in the starting position for the entrance half cycle (i.e.,  $\phi$  corresponds to a  $g=g_{\max}$ , refer to eq. (18)) and all kinematic properties are computed for this position. The position of the escape wheel is then indexed by an amount DELPHI (.01 radians), and the kinematic properties are recomputed for this new position. This process is repeated until the entrance half cycle is completed (i.e., corresponds to  $g=0$ , refer to eq. (22)). The escapement is then placed in the starting position for the exit phase, and the above operation is repeated for the entire range of exit positions.

The program consists of four basic sections. In the first, the input data is read in. Below is a listing of the input parameters and their definitions. These are read in on a single card, with a format of 6F10.5. All of the input information is available from the engineering drawings of the escapement components.

<u>Parameter</u>	<u>Explanation</u>
A	Distance between pivots of escape wheel and pallet
B	Escape wheel radius
C	Pallet radius to center of pallet pin (equal on top and on bottom)
R	Pallet pin radius (equal on top and bottom)
ALPHA	Escape wheel tooth half angle
DELTA	Angle between escape wheel teeth

The program will perform calculations for four different values of the coefficient of friction ( $MU(1)$ ,  $MU(2)$ ,  $MU(3)$ ,  $MU(4)$ ). These are read in on the second, and last, data card, in a format of 4F10.3. This will enable the user to determine the sensitivity of the escapement to friction.

The next section determines the quantities  $g_{\max}$  ( $G_{\max}$ ), the starting positions  $\phi_{M1,2}$  for the entrance half cycle ( $\phi_{HIEN}$ ), and exit half cycle ( $\phi_{HIEX}$ ) and the end position  $\phi_{01,2}$  of the entrance half cycle ( $\phi_{HIFEN}$ ) and exit half cycle ( $\phi_{HIFEX}$ ).



The last two sections compute the values of the kinematic parameters for the entrance and exit half cycles. At the beginning of each section, the program calls subroutine CALCUL. This subroutine determines the value of  $g$  and the pallet angle  $\psi$  for the position which will be analyzed next. With this information the program is then able to compute the instantaneous velocity ratio (QN), the rate of change of the instantaneous velocity ratio with respect to escape wheel angle (QNPRIM), and the friction corrected moment arms (AW,AP), the friction corrected angle (PSIF) and the efficiency (EFF) for each value of the coefficient of friction at each position of the entrance and exit half cycles. These quantities are printed out in tabular form, as shown in the sample output of appendix B.

#### SAMPLE CASE-M125A1 BOOSTER PIN PALLET ESCAPEMENT

The pin pallet escapement of the M125A1 Booster was analyzed as a sample application of this program. A drawing of this escapement is presented in figure 10. Nominal dimensions for the escapement geometry were used for input, and these are listed below, along with the four values of the coefficient of friction to be used in this study. The program output is given in appendix B, and is discussed below.

<u>Input parameter</u>	<u>Dimension</u>
A	.5182 cm (.204 in.)
B	.4877 cm (.192 in.)
C	.1991 cm (.0784 in.)
R	.0362 cm (.01425 in.)
ALPHA	51.0000°
DELTA	30.0000°
MU(I)	.1, .2, .3, .4

The position of the escape wheel when coupled motion first begins (corresponding to  $g=g_{max}$ ) is given by  $\phi_{M1,2}$ . For this escapement, these values were found to be

$$\phi_{M1} = 142.580^\circ$$

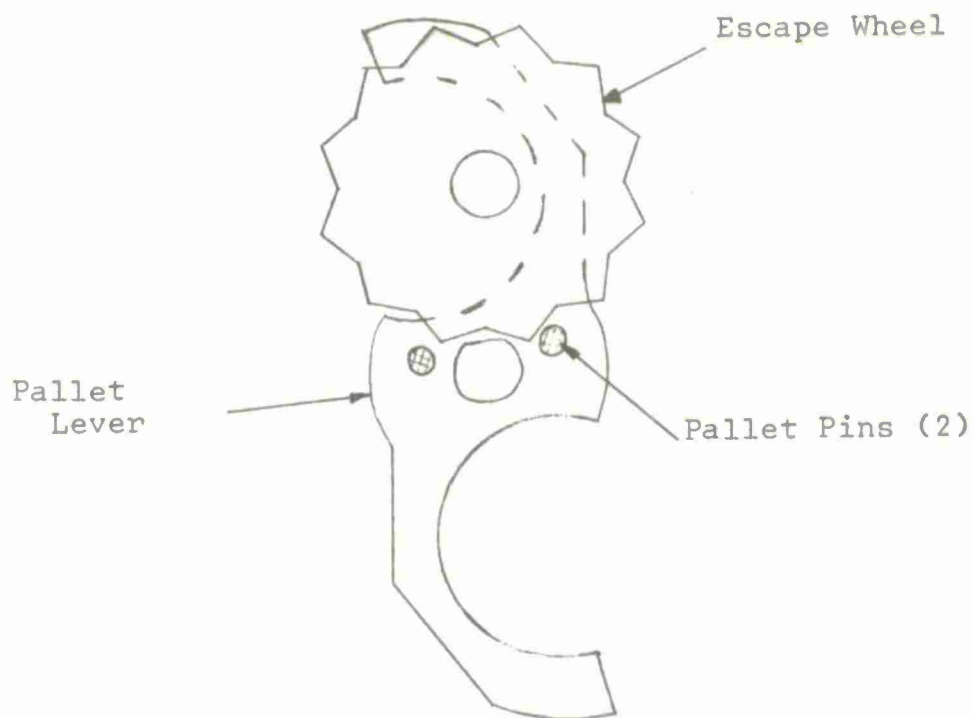


Figure 10. M125A1 booster pin pallet escapement.

for the entrance cycle, and

$$\phi_{M2} = 187.420^\circ$$

for the exit cycle.

The escape wheel angles  $\phi_{01,2}$  corresponding to the position when the pallet pin leaves the escape wheel tooth (i.e.,  $g=0$ ), were computed to be

$$\phi_{01} = 155.185^\circ$$

for entrance engagement, and

$$\phi_{02} = 199.452^\circ$$

for exit engagement.

Thus, during the entrance half cycle, the escape wheel rotates  $12.6^\circ$  and during the exit half cycle it rotates  $12.0^\circ$ .

### Velocity Ratio

Figures 11 and 12 depict the instantaneous angular velocity ratio between the pallet and the escape wheel as a function of the escape wheel position. Note that as this ratio increases the angular velocity of the pallet with respect to the escape wheel decreases. For entrance engagement, this ratio ranged from 1.084 at the beginning of the half cycle to 1.709 at the end. Thus, in entrance, the pallet angular velocity decreases as the pin approaches the escape wheel tip. For exit, this ratio was determined to be .970 at the starting position of the half cycle, and 2.213 at the end of the half cycle. It can be seen that the pallet will have its highest angular velocity with respect to the escape wheel at the beginning of the exit half cycle, but will be slowest at the end of the exit half cycle.

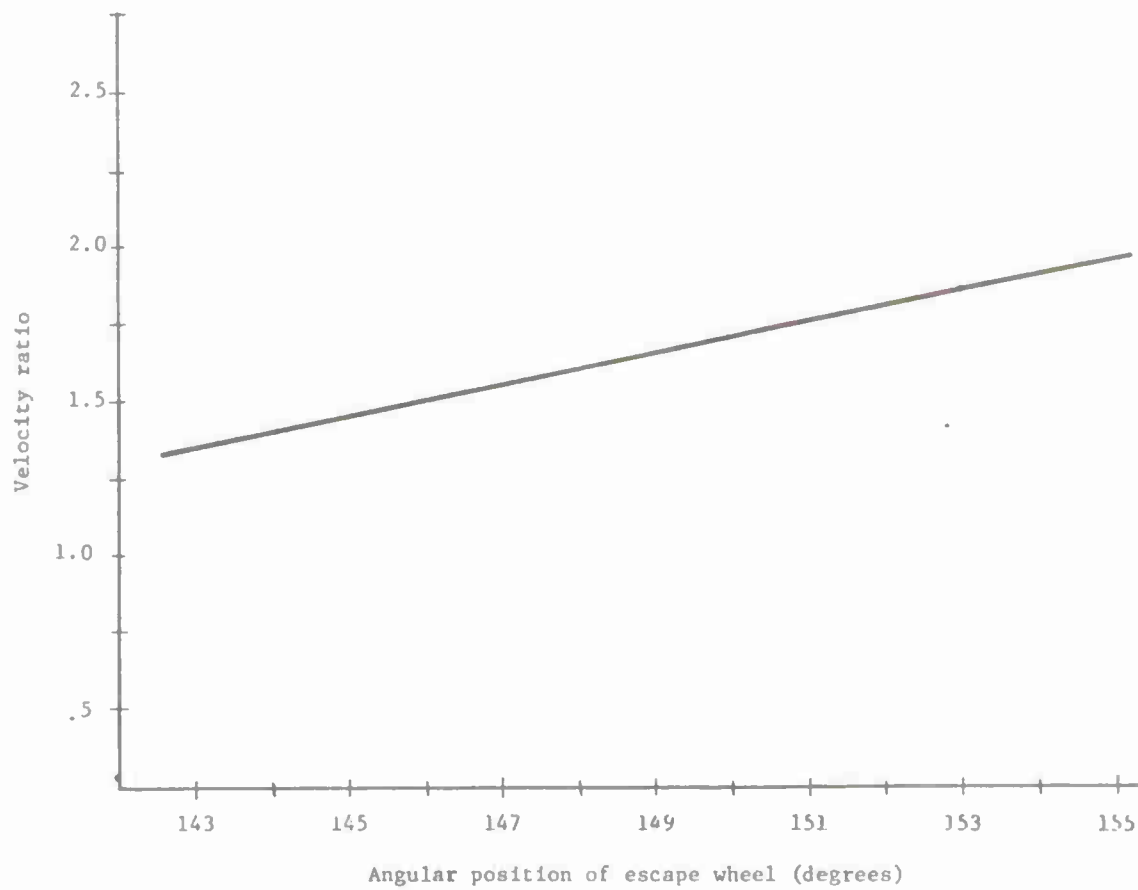


Figure 11. Velocity ratio - entrance engagement.

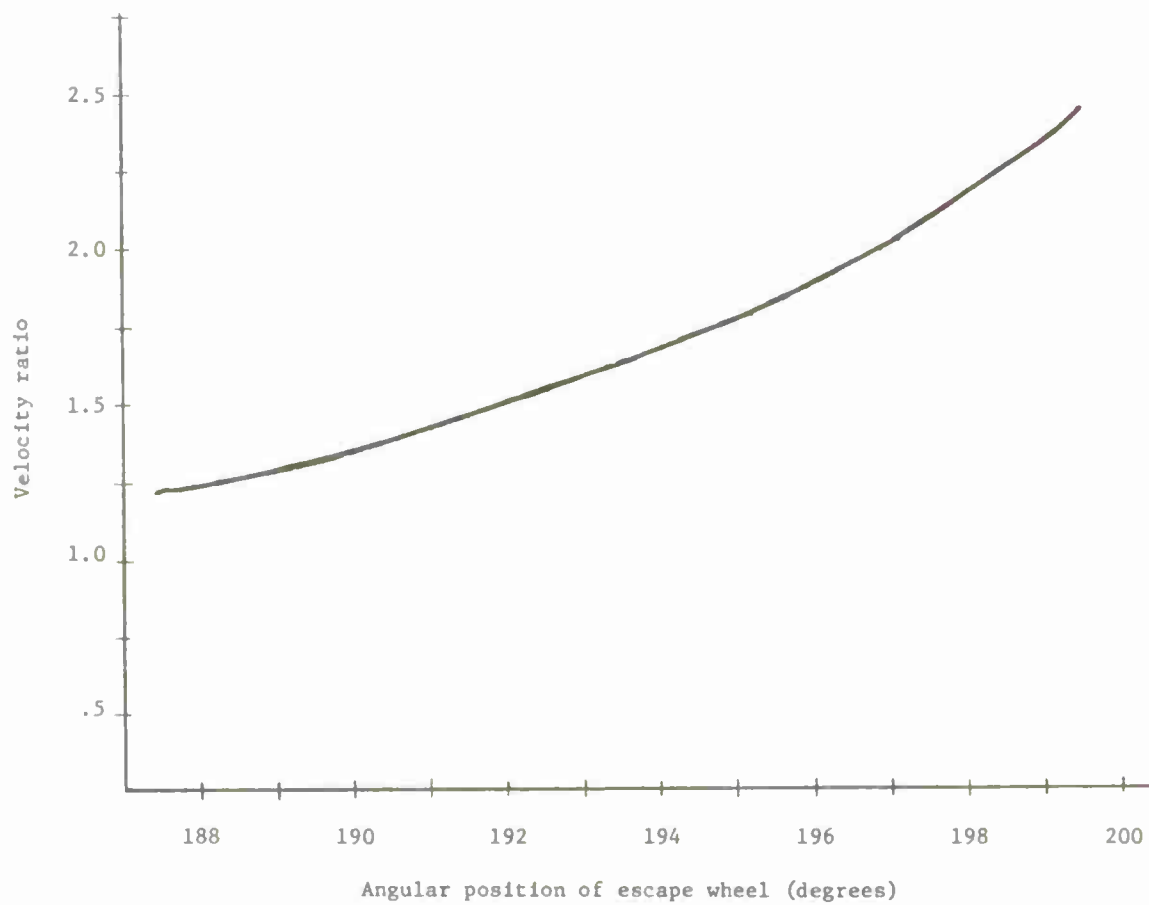


Figure 12. Velocity ratio - exit engagement

## Efficiency

The computations showed that the minimum values of the torque transmission efficiency occur at the beginning of the entrance half cycle (see fig. 13). These values were determined to be 76.2%, 59.4%, 46.8%, and 37.0%, for coefficients of friction of .1, .2, .3, and .4 respectively. The peak efficiency for entrance engagement occurred at the end of the half cycle, where the pallet pin contacted the tip of the escape wheel tooth. Values here were computed to be 82.8%, 69.1%, 57.8%, and 48.4% for the above coefficients of friction.

Efficiencies in exit (fig. 14) were found to be higher than those in entrance. At the beginning of this half cycle values attained were 82.0%, 69.3%, 59.8%, and 52.4%. The maximum values of the torque transmission efficiency, which occurred at the intermediate position of the exit half cycle, were 83.1%, 70.3%, 60.5%, and 52.8%, for the four friction coefficients. At the final pallet pin position, the efficiencies decreased to values of 81.9%, 67.5%, 55.6%, and 45.8%.

## Moment Arms

Figures 15 and 16 show the variation of the output and input force moment arms, as a function of the angular position of the escape wheel, for entrance engagement. In the absence of friction, values of the output force moment arm (A1) ranged from .185 cm (.073 in.) to .304 cm (.120 in.). Minimum friction corrected output force moment arms (AW) had values of .221 cm (.087 in.), .257 cm (.101 in.), .287 cm (.113 in.), and .312 cm (.123 in.) for coefficients of friction of .1, .2, .3, and .4 respectively. Maximum values were .343 cm (.135 in.), .373 cm (.147 in.), .401 cm (.158 in.), and .424 cm (.167 in.). Variations in the input force moment arms were not as great as those in the output force moment arms. Values for the uncorrected (no friction) input force moment arms (D1) ranged from .170 cm (.067 in.) to .178 cm (.070 in.). Minimum values of the friction corrected input force moment arms were .155 cm (.061 in.), .140 cm (.055 in.), .124 cm (.049 in.), and .107 cm (.042 in.). Maximum values were .165 cm (.065 in.), .152 cm (.060 in.), .137 cm (.054 in.), and .119 cm (.047 in.). In all cases, the minimum values occurred at the start of the entrance half cycle, and the maximum values occurred at the end of the entrance half cycle.

In a similar manner, figure 17 shows the variation of the input force moment arms, as a function of the angular position of the escape wheel, for exit engagement. Upon inspection of the computer output, it will be seen that the values of the output force moment arms for exit engagement are identical to those for entrance engagement.

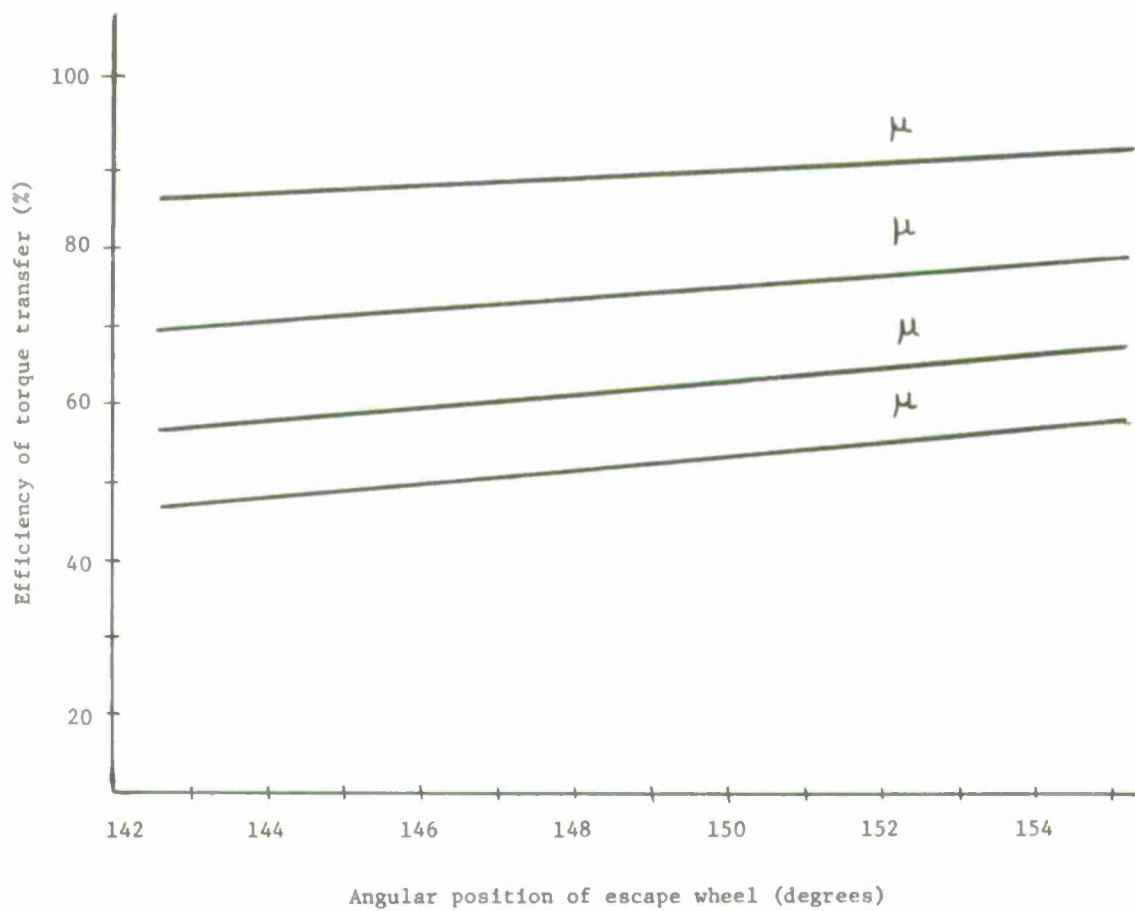


Figure 13. Efficiency - entrance engagement.

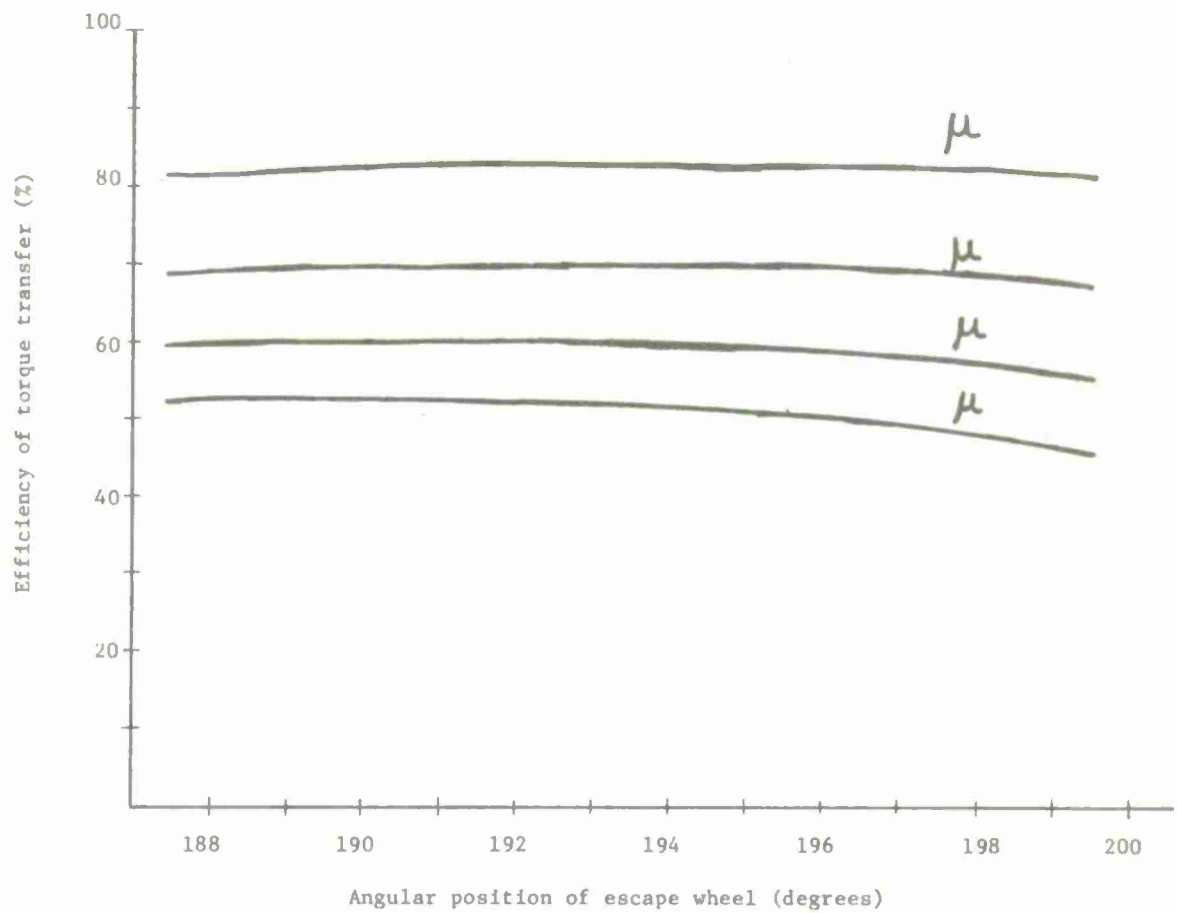


Figure 14. Efficiency - exit engagement.



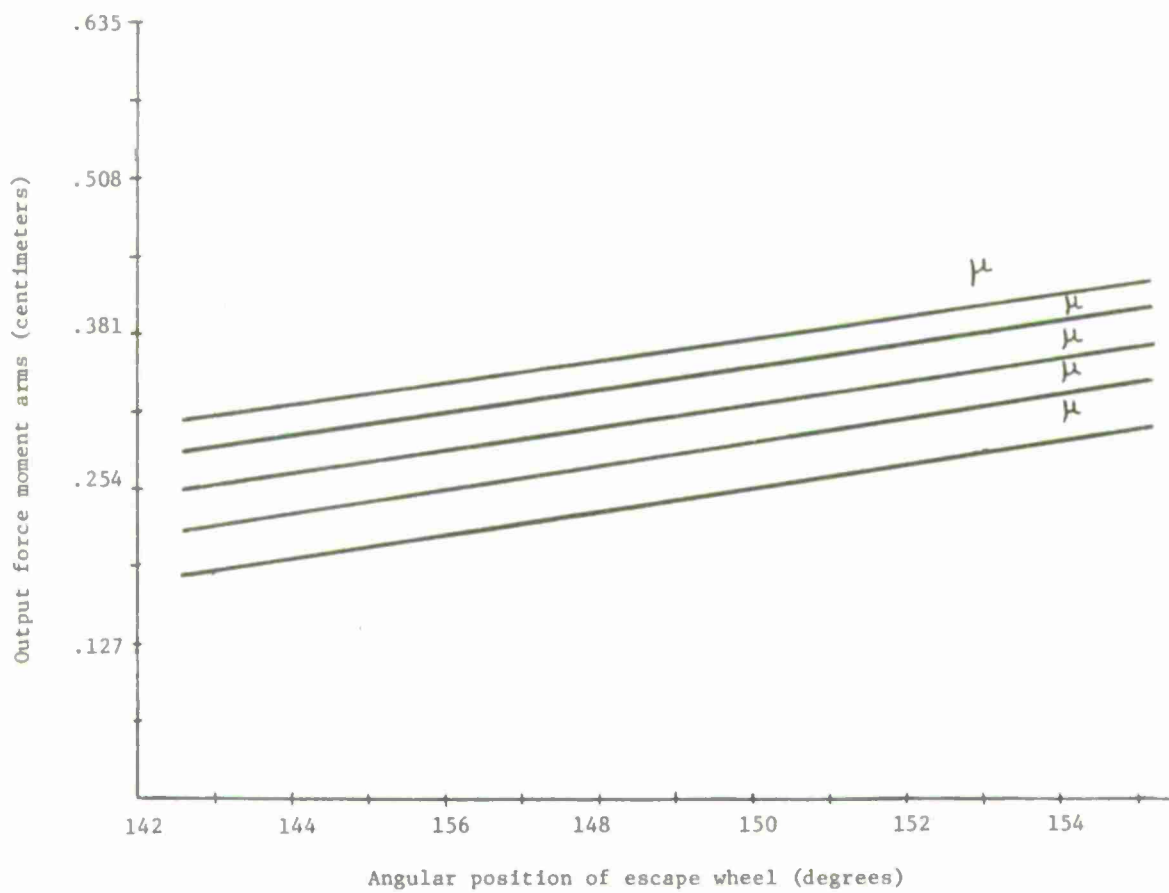


Figure 15. Output force moment arms - entrance engagement.

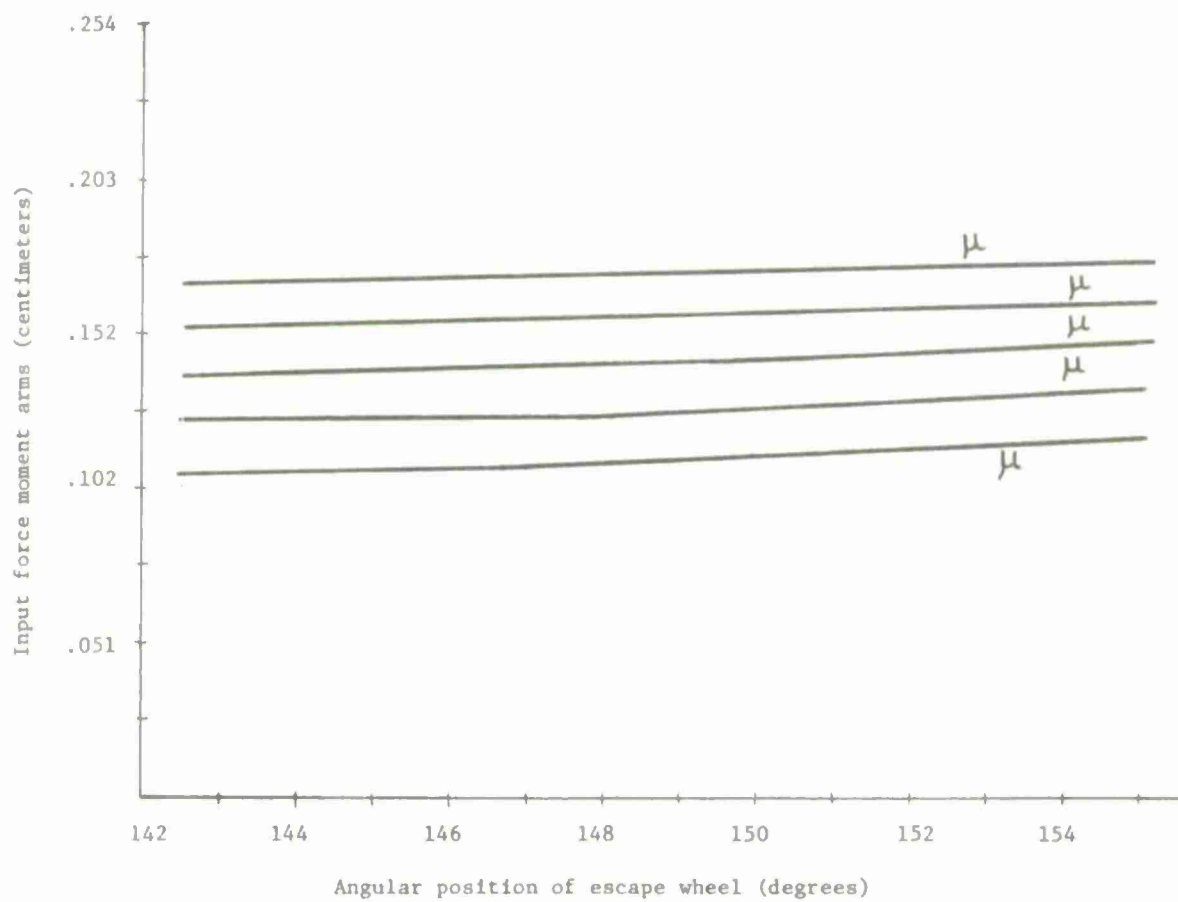


Figure 16. Input force moment arms - entrance engagement.

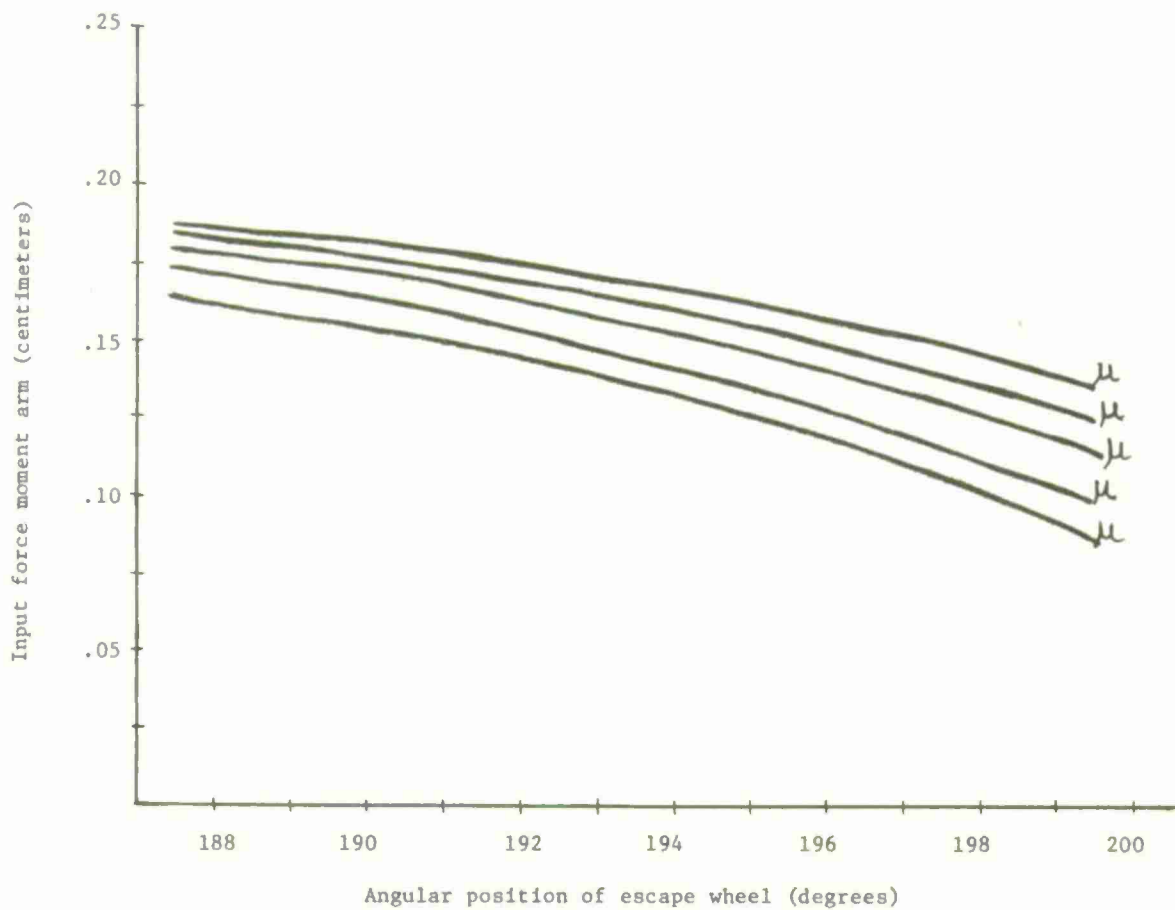


Figure 17. Input force moment arm - exit engagement.

The magnitude of the uncorrected input force moment arm ranged from .191 cm (.075 in.) to .137 cm (.054 in.). Maximum values of the friction corrected input force moment arms were .188 cm (.074 in.), .183 cm (.072 in.), .175 cm (.069 in.), and .168 cm (.066 in.). Minimum values were .127 cm (.050 in.), .114 cm (.045 in.), .102 cm (.040 in.), and .086 cm (.034 in.). For exit engagement, the minimum values occurred at the end of the half cycle, and the maximum values occurred at the start of the half cycle.

## EFFECT OF VARIATION IN CENTER DISTANCE

Due to the possibility of two different modes of contact in the exit phase, a study was undertaken to determine the effects of variations in the pivot center distance on the other system parameters. This was accomplished by exercising the computer program using a center distance of  $A = .582$  cm (.229 in.) representing an increase in the nominal value of 12%, and for  $A = .503$  cm (.198 in.) corresponding to a decrease of 3%. Larger percent decreases in the center distance could not be investigated, as interference between the pallet pins and the escape wheel teeth would occur. All other input parameters remained at their nominal values. The computer output for the first case is presented in appendix C and for the latter case in appendix D. Table 1 summarizes the results of this study.

### Increased Center Distance

Increasing the center distance resulted in a decrease in angular displacement of the entrance half cycle while increasing the displacement of the exit half cycle. Table 1 shows that entrance engagement for an extended center distance begins at a later position than it does for the nominal configuration, while exit engagement begins at an earlier position. The escape wheel rotates only  $9.74^\circ$  during the entrance half cycle (compared to  $12.6^\circ$  for the nominal center distance), while it rotates  $14.9^\circ$  during the exit half cycle (compared to  $12.0^\circ$ ).

The instantaneous angular velocity ratios for the escapement with increased center distance were higher than those of the nominal configuration in the entrance half cycle, but lower than those of the nominal configuration in the exit half cycle. For entrance engagement, the ratio ranged from 1.602, at the beginning of the half cycle, to 2.192 at the end. In exit, the range was .934 to 1.718. This indicates that the pallet would have a lower angular velocity in entrance and a higher angular velocity in exit than in the nominal configuration. Furthermore, although the pallet would still have its highest

Table 1. Effects of variations in center distance\*

	Nominal C.D. 0.518(0.204)		Increased C.D. 0.582(0.229)		Decreased C.D. 0.503(0.198)	
	Entrance engagement					
Angle start of coupled motion ( $\phi_M$ )	142.580°		147.860°		141.690°	
Angle at end of coupled motion ( $\phi_{O1}$ )	155.185°		157.600°		154.870°	
Velocity ratio	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Efficiency		1.084	1.709	2.192	1.034	1.651
	$\mu=.1$	.762	.828	.776	.772	.837
	$\mu=.2$	.594	.691	.596	.611	.707
	$\mu=.3$	.468	.578	.449	.490	.600
	$\mu=.4$	.370	.484	.326	.397	.511
Output force moment arms	$\mu=0.0$	.185(.073)	.305(.120)	.305(.120)	.185(.073)	.305(.120)
	$\mu=.1$	.221(.087)	.343(.135)	.343(.135)	.221(.087)	.343(.135)
	$\mu=.2$	.257(.101)	.373(.147)	.373(.147)	.257(.101)	.373(.147)
	$\mu=.3$	.287(.113)	.401(.158)	.401(.158)	.287(.113)	.401(.158)
	$\mu=.4$	.312(.123)	.424(.167)	.424(.167)	.312(.123)	.424(.167)
Input force moment arms	$\mu=0.0$	.170(.067)	.178(.070)	.140(.055)	.178(.070)	.185(.073)
	$\mu=.1$	.155(.061)	.165(.065)	.094(.037)	.165(.065)	.173(.068)
	$\mu=.2$	.140(.055)	.152(.060)	.074(.029)	.150(.059)	.160(.063)
	$\mu=.3$	.124(.049)	.137(.054)	.053(.021)	.135(.053)	.145(.057)
	$\mu=.4$	.107(.042)	.119(.047)	.033(.013)	.119(.047)	.132(.052)

\*All dimensions are in centimeters; dimensions in parentheses are in inches.

Table 1. (Continued)

		Nominal C.D. 0.518(0.204)		Increased C.D. 0.582(0.229)		Decreased C.D. 0.503(0.198)	
		Exit engagement					
Mode of contact		Mode 1		Mode 2-Mode 1		Mode 1	
Angle at start of coupled motion ( $\varphi_{M2}$ )		187.420°		182.140°		188.310°	
Angle at end of coupled motion ( $\varphi_{O2}$ )		199.452°		197.040°		199.770°	
Velocity ratio		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
		0.970	2.213	0.934	1.718	1.000	2.420
Efficiency	$\mu=.1$	.820	.831	.855	.867	.806	.822
	$\mu=.2$	.693	.703	.752	.764	.650	.688
	$\mu=.3$	.598	.605	.662	.684	.523	.586
	$\mu=.4$	.524	.528	.587	.621	.416	.506
Output force moment arms	$\mu=0.0$	.185(.073)	.305(.120)	.185(.073)	.305(.120)	.185(.073)	.305(.120)
	$\mu=.1$	.221(.087)	.343(.135)	.221(.087)	.340(.134)	.221(.087)	.340(.134)
	$\mu=.2$	.257(.101)	.373(.147)	.257(.101)	.373(.147)	.257(.101)	.373(.147)
	$\mu=.3$	.287(.113)	.401(.158)	.287(.113)	.401(.158)	.287(.113)	.401(.158)
	$\mu=.4$	.312(.123)	.424(.167)	.312(.123)	.424(.167)	.312(.123)	.424(.167)
Input force moment arms	$\mu=0.0$	.137(.054)	.191(.075)	.178(.070)	.198(.078)	.124(.049)	.185(.073)
	$\mu=.1$	.127(.050)	.188(.074)	.170(.067)	.203(.080)	.114(.045)	.180(.071)
	$\mu=.2$	.114(.045)	.183(.072)	.163(.064)	.206(.081)	.099(.039)	.173(.068)
	$\mu=.3$	.102(.040)	.175(.069)	.155(.061)	.206(.081)	.086(.034)	.165(.065)
	$\mu=.4$	.086(.034)	.168(.066)	.145(.057)	.206(.081)	.074(.029)	.157(.062)

angular velocity at the beginning of the exit half cycle, its lowest angular velocity would now occur at the end of the entrance half cycle.

Efficiencies in the entrance half cycle were much lower than those for the nominal configuration. Although the peak efficiency for entrance still occurred at the end of the half cycle, values were only 77.6%, 59.6%, 44.9%, and 32.6%. Minimum values, which occur at the beginning of the half cycle, were 68.7%, 46.5%, 30.0%, and 17.1%. It may be concluded that based on these reduced values of the efficiency, increasing center distances may result in undesirable torque transmission efficiencies.

The overall efficiencies in exit engagement were much higher than those for the nominal configuration. At the beginning of the half cycle values were 85.5%, 75.2%, 67.5%, and 61.5%. Peak values were 86.7%, 76.4%, 68.4%, and 62.1%, dropping off to 86.2%, 75.2%, 66.2%, and 58.7% at the end of the half cycle. While the effect of the increased center distance was to yield very high values of efficiency in the exit half cycle, this benefit was offset by the extremely low efficiencies encountered during entrance engagement.

Table 1 illustrates that the magnitudes of the output force moment arms did not vary from nominal values for both entrance and exit engagement, for the increased center distance. However, for entrance engagement, the magnitudes of the input force moment arms were much smaller than those of the nominal configuration but larger than those of the nominal configuration for exit engagement.

Finally, referring to the computer output of appendix C, it may be seen that mode 2 contact will occur for approximately one half of the exit phase. This is indicated by the negative values of  $C_1$  (fig. 9).

### Decreased Center Distance

The program was exercised using the minimum value of the center distance that does not cause interference .503 cm (.198 in.).

Whereas increasing the center distance decreased the length of entrance engagement, and increased the length of exit engagement, decreasing the center distance had the opposite effect (table 1). The escape wheel would now rotate  $13.18^\circ$  during the entrance half cycle, compared to the  $12.6^\circ$  rotation of the nominal configuration, and would rotate  $11.46^\circ$  during exit, as compared to  $12.0^\circ$  for the nominal configuration.

The effects of decreasing the center distance on the instantaneous angular velocity ratio were also opposite to those produced by an increased center distance. For entrance positions, the velocity ratios were lower than those of the nominal configuration, ranging from 1.034 at the start of the half cycle, to 1.651 at the end of the half cycle. Exit angular velocity ratios were higher than those of the nominal configuration, ranging from 1.000 to 2.420. Similar to the nominal configuration, the velocity of the pallet would be lower in exit, than in entrance, its highest velocity would be reached at the beginning of the exit phase, and the pallet would have its lowest velocity at the end of the exit phase.

Efficiencies in entrance were higher than those for the nominal configuration. Peak efficiencies still occurred at the end of the half cycle, with values of 83.7%, 70.7%, 60.0%, and 51.1%. Minimum values at the start of the entrance phase, were 77.2%, 61.1%, 49.0%, and 39.7%. Efficiencies in exit, however, were less than those for the nominal configuration. Peak values were 82.2%, 68.8%, 58.5%, and 50.6%. Minimum values, at the end of the exit phase were 80.6%, 65.0%, 52.3%, and 41.6%. These values do not represent a significant change in the ability of the escapement as a torque transfer mechanism.

Referring to table 1, it can be seen that, as in the case of increased center distance, the magnitudes of the output force moment arms did not vary from nominal values for both entrance and exit engagements. The magnitudes of the input force moment arms, however, were greater than those of the nominal configuration for entrance, and less than those of the nominal configuration for exit.

Lastly, the computer output of appendix D, shows that, as in the nominal configuration, only mode 1 contact will occur in the exit phase for the decreased center distance.

## CONCLUSIONS

An analytic tool has been developed which can be used as a guide in the design of new pin pallet escapements or in the improvement of existing escapements. This can be accomplished by exercising the computer program to make parametric studies of proposed or existing designs instead of recourse to trial and error testing. For example, this work has been used to discover the significant influence the center distance has on the torque transmission efficiency of the pin pallet escapement.



## RECOMMENDATIONS

It is recommended that the analytic tool which has been developed be applied when designing new or improving existing pin pallet runaway escapements. It is further recommended that this analysis be integrated with other studies to formulate a kinematic simulation of a complete S&A mechanism.

## REFERENCE

1. G. G. Lowen and F. R. Tepper, "Dynamics of the Runaway Escapement," Fuze Development Branch Information Report No. 94, February 1977.

APPENDIX A

COMPUTER PROGRAM







```
      J = J + 1
      PHI(J) = PHI(J-1) * DELPHI
      GO TO 6
110      C
      C EXIT
      C
      C 90 ONP=0.0
      C 9 PHI(J) = PHIEX
      C 10 IF(PHI(J) .GT. PHIFEX) GO TO 13
      C CALL CALCUL(A,R,C,R,ALPHAR,PHI(J),G,PSI)
      C A1 = R * COS(ALPHAR) * G
      C C1 = -(R * C * SIN(PHI(J)) - ALPHAR * PSI)
      C D1 = C * COS(PHI(J)) - ALPHAR * PSI
      C R = SORT(A1 * A1 + B1 * B1)
      C RP = SORT(C1 * C1 + D1 * D1)
      C CC = ARS(C1)
      C DD = ABS(D1)
      C ON = A1 / DD
      C NO(J) = A1 / DD
      C ONN = ON - ONP
      C ONPRIM(J) = ONN / (PHI(J) - PHI(J-1))
      C IF(ONP .EQ. 0.1) ONPRIM(J) = 0.0
      C ONP = ON
130      IF(C1 .LT. 0.0160 TO 30
      C TAU = PI - ATAN2(DD,CC)
      C TAUW = ATAN2(B1,A1)
      C GO TO 14
      C 30 TAU = ATAN2(CC,DD)
      C TAUW = ATAN2(A1,B1)
135      18 PSIP = PI - PHI(J) * ALPHAR
      C 00 I1 1 = 1.4
      C X1 = ATAN2(MU(I),1.)
      C IF(C1 .LT. 0.0160 TO 31
      C AP(I) = RP * SIN(TAU * X1)
      C AW(I) = RW * COS(TAU * X1)
      C GO TO 23
      C 31 AW(I) = RW * SIN(TAU * X1)
      C AP(I) = RP * COS(TAU * X1)
      C 23 PSIF(I) = PSIP - X1
      C IF(C1 .LT. 0.0160 TO 32
      C EFF(I,J) = (1. - MU(I) * CC / DD) / (1. - MU(I) * B1 / A1)
      C GO TO 11
      C 32 EFF(I,J) = (1. - MU(I) * CC / DD) / (1. - MU(I) * B1 / A1)
      C 11 CONTINUE
      C PSIP0 = PSIP / Z
      C PH10 = PHI(J) / Z
      C PSIF10 = PSIF(1) / Z
      C PSIF20 = PSIF(2) / Z
      C PSIF30 = PSIF(3) / Z
      C PSIF40 = PSIF(4) / Z
      C WRITE(6,12) PH10, A1, D1, AP(1), AP(2), AP(3), AP(4), AW(1), AW(2), AW(3),
      C 1 AW(4), PSIP0, PSIF10, PSIF20, PSIF30, PSIF40, C1
      C 12 FORMATT(F8.3,2X,F5.3,2X,F5.3,2X,F5.3,2X,F5.3,2X,F5.3,2X),
      C 12 FORMATT(F8.3,2X,F5.3,2X,F5.3,2X,F5.3,2X,F5.3,2X),
```

PROGRAM PINPAL	74/74	OPT=1	FTN 4.6.420	01/17/78	13.28.04	PAGE 4
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160 IF 6.2.1X.4(1X.F6.2).1X.FX11.5X.F5.3)
      J = J + 1
      PHI(J) = PHI(J-1) + DELPHI
      GO TO 10
163 WRITE(6,14)
164 FORMAT(1X,PHI.12X.0FFICIENCY.9X.0VFLOCITY RATIO.5X.0N PRIME.
1/0 DEG.1X.0MU(1).2X.0MU(2).2X.0MU(3).2X.0MU(4).)
      JEND = J - 1
      DO 16 J = 1,JEND
      PHIO = PHI(J)/2
      WRITE(6,15)PHIO.EFF(1.1).EFF(2.J).EFF(3.3).EFF(4.J).NO(J).ONPRIM(J)
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1 SUBROUTINE CALCUL(A,B,C,R,ALPHAR,PHI),G,PSI)

REAL K

A = 2.0\*(B\*COS(ALPHAR) - A\*COS(PHI) - ALPHAR))

K = A\*\*2 + B\*\*2 + C\*\*2 - 2.0\*B\*COS(ALPHAR) + 2.0\*A\*B

1/COS(PHI) = 2.0\*A\*B\*COS(PHI) - ALPHAR

G1 = (-M + SORT(M\*\*2 - 4.0\*K))/2.0

G2 = (-M - SORT(M\*\*2 - 4.0\*K))/2.0

IF (ABS(G1) .LT. ABS(G2)) GO TO 1

G = G2

GO TO 2

1 G = G1

2 P = B\*COS(PHI) + G\*SIN(PHI) - ALPHAR + B\*COS(PHI) - ALPHAR

PSI = ASIN(P/C)

IF (PSI .LT. 0.0) GO TO 3

GO TO 4

3 PSI = 2.0314159 - ABS(PSI)

4 RETURN

END





## APPENDIX B

### COMPUTER OUTPUT FOR NOMINAL CONFIGURATION



A = .20400 B = .19200 C = .07840 R = .01425 ALPHA = 51.00 DELTA = 30.00

MU(1) = .100 MU(2) = .200 MU(3) = .300 MU(4) = .400

PM DEG	AI	AT	AP			AW			PSIP			PSIF			CI	
			MU(1)	MU(2)	MU(3)	MU(4)	MU(1)	MU(2)	MU(3)	MU(4)	MU(1)	MU(2)	MU(3)	MU(4)		
142.580	.073	.067	.061	.055	.049	.042	.087	.101	.113	.123	88.42	82.71	77.11	71.72	66.62	ENTRANCE -.055
143.153	.075	.067	.061	.055	.049	.042	.089	.103	.115	.125	87.85	82.14	76.54	71.15	66.05	ENTRANCE -.055
143.724	.077	.067	.061	.055	.049	.042	.091	.105	.117	.127	87.27	81.56	75.96	70.57	65.47	ENTRANCE -.055
144.299	.079	.067	.062	.055	.049	.042	.094	.107	.119	.129	86.70	80.99	75.39	70.00	64.90	ENTRANCE -.054
144.872	.081	.067	.062	.055	.049	.042	.096	.109	.121	.131	86.13	80.42	74.82	69.43	64.33	ENTRANCE -.054
145.445	.083	.067	.062	.056	.049	.043	.098	.111	.123	.133	85.56	79.84	74.25	68.86	63.75	ENTRANCE -.054
146.018	.085	.068	.062	.056	.049	.043	.100	.113	.125	.135	84.98	79.27	73.67	68.28	63.18	ENTRANCE -.054
146.591	.088	.068	.062	.056	.049	.043	.102	.115	.127	.137	84.41	78.70	73.10	67.71	62.61	ENTRANCE -.054
147.164	.090	.068	.062	.056	.050	.043	.104	.117	.129	.139	83.84	78.13	72.53	67.14	62.03	ENTRANCE -.054
147.737	.092	.068	.062	.056	.050	.043	.106	.119	.131	.141	83.26	77.55	71.95	66.56	61.46	ENTRANCE -.053
148.309	.094	.068	.062	.056	.050	.043	.108	.121	.133	.143	82.69	76.94	71.38	65.99	60.89	ENTRANCE -.053
148.882	.096	.068	.063	.057	.050	.044	.111	.124	.135	.145	82.12	76.41	70.81	65.42	60.32	ENTRANCE -.053
149.455	.098	.068	.063	.057	.050	.044	.113	.126	.137	.147	81.54	75.83	70.23	64.85	59.74	ENTRANCE -.053
150.028	.101	.069	.063	.057	.051	.044	.115	.128	.139	.149	80.97	75.26	69.66	64.27	59.17	ENTRANCE -.052
150.601	.103	.069	.063	.057	.051	.045	.117	.130	.141	.151	80.40	74.69	69.09	63.70	58.60	ENTRANCE -.052
151.174	.105	.069	.063	.057	.051	.045	.119	.132	.143	.153	79.83	74.12	68.52	63.13	58.02	ENTRANCE -.052
151.747	.107	.069	.064	.058	.052	.045	.121	.134	.146	.155	79.25	73.54	67.94	62.55	57.45	ENTRANCE -.051
152.320	.109	.069	.064	.058	.052	.046	.124	.137	.148	.157	78.68	72.97	67.37	61.98	56.88	ENTRANCE -.051
152.893	.112	.070	.064	.058	.052	.046	.126	.139	.150	.159	78.11	72.40	66.80	61.41	56.31	ENTRANCE -.050
153.466	.114	.070	.064	.059	.052	.046	.128	.141	.152	.161	77.53	71.82	66.22	60.43	55.73	ENTRANCE -.050
154.039	.116	.070	.065	.059	.053	.047	.130	.143	.154	.163	76.96	71.25	65.65	60.26	55.16	ENTRANCE -.050
154.612	.118	.070	.065	.059	.053	.047	.133	.145	.156	.165	76.39	70.68	65.08	59.69	54.59	ENTRANCE -.049
155.185	.120	.070	.065	.060	.054	.047	.135	.147	.158	.167	75.82	70.10	64.51	59.12	54.01	ENTRANCE -.049
155.758	.123	.075	.074	.072	.069	.046	.087	.101	.113	.123	43.58	37.87	32.27	26.88	21.78	EXIT
156.331	.125	.075	.073	.071	.068	.045	.089	.102	.114	.125	43.01	37.30	31.70	26.31	21.21	EXIT
156.904	.127	.074	.073	.070	.068	.044	.091	.104	.116	.126	42.43	36.72	31.12	25.73	20.63	EXIT
157.477	.129	.073	.072	.069	.067	.043	.093	.106	.118	.128	41.85	36.15	30.55	25.16	20.06	EXIT
158.050	.131	.073	.071	.069	.066	.042	.095	.108	.120	.130	41.29	35.58	29.98	24.59	19.49	EXIT
158.623	.133	.072	.070	.068	.065	.041	.097	.110	.122	.132	40.72	35.00	29.41	24.02	18.91	EXIT
159.196	.135	.072	.069	.067	.063	.040	.099	.112	.124	.134	40.14	34.43	28.83	23.44	18.34	EXIT
159.769	.137	.071	.069	.066	.062	.039	.101	.114	.126	.136	39.57	33.86	28.26	22.87	17.77	EXIT
160.342	.139	.071	.069	.066	.062	.038	.103	.116	.128	.138	39.00	33.29	27.69	22.30	17.19	EXIT
160.915	.141	.070	.068	.065	.061	.037	.105	.118	.130	.139	38.42	32.71	27.11	21.72	16.62	EXIT
161.488	.143	.069	.066	.062	.059	.036	.107	.120	.132	.141	37.85	32.14	26.54	21.15	16.05	EXIT
162.061	.145	.068	.065	.061	.057	.035	.109	.122	.134	.143	37.28	31.57	25.97	20.58	15.48	EXIT
162.634	.147	.067	.064	.060	.056	.034	.111	.124	.136	.146	36.70	30.99	25.39	20.01	14.90	EXIT
163.207	.149	.066	.063	.059	.055	.033	.113	.126	.138	.148	36.13	30.42	24.82	19.43	14.33	EXIT
163.780	.151	.065	.062	.058	.054	.032	.114	.127	.139	.150	35.56	29.85	24.25	18.86	13.76	EXIT
164.353	.153	.064	.061	.057	.053	.031	.116	.129	.140	.151	34.99	29.27	23.68	18.29	13.18	EXIT
164.926	.155	.063	.060	.056	.052	.030	.118	.131	.142	.152	34.41	28.70	23.10	17.71	12.61	EXIT
165.499	.157	.062	.059	.055	.051	.029	.121	.134	.145	.154	33.84	28.13	22.53	17.14	12.04	EXIT
166.072	.159	.061	.057	.053	.049	.028	.123	.136	.147	.157	33.27	27.56	21.96	16.57	11.47	EXIT
166.645	.161	.060	.056	.052	.048	.027	.124	.137	.148	.159	32.69	26.98	21.38	15.99	10.89	EXIT
167.218	.163	.059	.055	.051	.047	.026	.126	.139	.150	.161	32.12	26.41	20.81	15.42	10.32	EXIT
167.791	.165	.058	.054	.050	.046	.025	.128	.141	.152	.163	31.55	25.84	20.24	14.85	9.75	EXIT
168.364	.167	.057	.053	.049	.045	.024	.130	.143	.154	.167	30.97	25.26	19.66	14.27	9.17	EXIT
168.937	.169	.056	.052	.048	.044	.023	.133	.146	.157	.169	30.40	24.69	19.09	13.70	8.59	EXIT
169.510	.171	.055	.051	.047	.043	.022	.135	.148	.159	.171	29.83	24.12	18.52	13.13	8.01	EXIT
170.083	.173	.054	.050	.046	.042	.021	.138	.151	.161	.173	29.26	23.55	17.95	12.54	7.42	EXIT

PHI NEG	MU(1)	MU(2)	EFFICIENCY MU(3)	MU(4)	VELOCITY RATIO	N PRIME
142.580	.762	.594	.468	.370	1.084	0.000
143.153	.766	.599	.473	.375	1.114	3.029
143.726	.770	.604	.478	.380	1.144	3.022
144.299	.773	.608	.484	.385	1.174	3.011
144.872	.777	.613	.489	.390	1.204	3.002
145.445	.780	.618	.494	.395	1.234	2.989
146.018	.783	.623	.499	.400	1.264	2.974
146.591	.786	.627	.504	.406	1.294	2.958
147.164	.790	.632	.509	.411	1.323	2.940
147.737	.793	.636	.514	.416	1.352	2.921
148.309	.796	.641	.519	.421	1.381	2.900
148.882	.799	.645	.524	.426	1.410	2.878
149.455	.802	.649	.529	.431	1.439	2.854
150.028	.804	.654	.534	.436	1.467	2.830
150.601	.807	.658	.539	.441	1.495	2.804
151.174	.810	.662	.544	.447	1.523	2.778
151.747	.813	.666	.549	.452	1.550	2.751
152.320	.815	.671	.554	.457	1.577	2.723
152.893	.818	.675	.559	.463	1.604	2.694
153.466	.821	.679	.564	.468	1.631	2.665
154.039	.823	.683	.568	.473	1.657	2.636
154.612	.826	.687	.573	.479	1.683	2.606
155.185	.828	.691	.578	.484	1.709	2.576
155.758	.830	.695	.583	.489	.970	0.000
156.331	.832	.699	.588	.494	1.001	3.114
156.904	.834	.703	.593	.499	1.034	3.237
157.477	.836	.707	.598	.504	1.068	3.371
158.050	.838	.711	.603	.509	1.103	3.518
158.623	.840	.715	.608	.514	1.140	3.680
159.196	.842	.719	.613	.519	1.173	3.859
159.769	.844	.723	.618	.524	1.213	4.056
160.342	.846	.727	.623	.529	1.261	4.274
160.915	.848	.731	.628	.534	1.307	4.516
161.488	.850	.735	.633	.539	1.354	4.787
162.061	.852	.739	.638	.544	1.405	5.089
162.634	.854	.743	.643	.549	1.460	5.429
163.207	.856	.747	.648	.554	1.518	5.812
163.780	.858	.751	.653	.559	1.580	6.247
164.353	.860	.755	.658	.564	1.649	6.744
164.926	.862	.759	.663	.569	1.721	7.315
165.499	.864	.763	.668	.574	1.801	7.976
166.072	.866	.767	.673	.579	1.889	8.748
166.645	.868	.771	.678	.584	1.985	9.657
167.218	.870	.775	.683	.589	2.092	10.740
167.791	.872	.779	.688	.594	2.213	12.046



## APPENDIX C

COMPUTER OUTPUT FOR NOMINAL CONFIGURATION  
WITH A = .582 CM (.229 IN.)





A = .22900 B = .19200 C = .07840 R = .01425 ALPHA = 51.00 DELTA = 30.00

MU(1) = .100 MU(2) = .200 MU(3) = .300 MU(4) = .400

DEG	AI	DI	AP	AW	PSIP	PSIF	C1
MU(1)	MU(2)	MU(3)	MU(4)	MU(1)	MU(2)	MU(3)	MU(4)
147.860	.073	.045	.037	.029	.021	.013	.123
148.133	.075	.046	.038	.030	.022	.015	.125
149.006	.078	.046	.038	.030	.022	.015	.125
149.579	.081	.047	.039	.031	.023	.016	.126
150.152	.084	.047	.039	.031	.023	.016	.126
150.724	.086	.048	.040	.032	.024	.016	.127
151.297	.089	.048	.040	.032	.024	.016	.127
151.870	.092	.049	.041	.033	.025	.017	.128
152.443	.095	.049	.042	.034	.026	.018	.129
153.016	.098	.050	.042	.034	.026	.019	.130
153.589	.100	.050	.043	.035	.027	.019	.131
154.162	.103	.051	.043	.036	.028	.020	.132
154.735	.106	.052	.044	.036	.028	.021	.133
155.308	.109	.052	.045	.037	.029	.022	.134
155.881	.112	.053	.045	.038	.030	.022	.135
156.454	.115	.054	.046	.038	.031	.023	.136
157.027	.117	.054	.047	.039	.032	.024	.137
157.600	.120	.055	.048	.040	.032	.025	.138
158.173	.123	.055	.048	.040	.032	.025	.138
158.746	.126	.056	.049	.041	.033	.026	.139
159.319	.129	.056	.049	.041	.033	.026	.139
159.892	.132	.057	.050	.042	.034	.027	.140
160.465	.135	.057	.050	.042	.034	.027	.140
161.038	.138	.058	.051	.043	.035	.028	.141
161.611	.141	.058	.051	.043	.035	.028	.141
162.184	.144	.059	.052	.044	.036	.029	.142
162.757	.147	.059	.052	.044	.036	.029	.142
163.330	.150	.060	.053	.045	.037	.030	.143
163.903	.153	.060	.053	.045	.037	.030	.143
164.476	.156	.061	.054	.046	.038	.031	.144
165.049	.159	.061	.054	.046	.038	.031	.144
165.622	.162	.062	.055	.047	.039	.032	.145
166.195	.165	.062	.055	.047	.039	.032	.145
166.768	.168	.063	.056	.048	.040	.033	.146
167.341	.171	.063	.056	.048	.040	.033	.146
167.914	.174	.064	.057	.049	.041	.034	.147
168.487	.177	.064	.057	.049	.041	.034	.147
169.060	.180	.065	.058	.050	.042	.035	.148
169.633	.183	.065	.058	.050	.042	.035	.148
170.206	.186	.066	.059	.051	.043	.036	.149
170.779	.189	.066	.059	.051	.043	.036	.149
171.352	.192	.067	.060	.052	.044	.037	.150
171.925	.195	.067	.060	.052	.044	.037	.150
172.498	.198	.068	.061	.053	.045	.038	.151
173.071	.201	.068	.061	.053	.045	.038	.151
173.644	.204	.069	.062	.054	.046	.039	.152
174.217	.207	.069	.062	.054	.046	.039	.152
174.790	.210	.070	.063	.055	.047	.040	.153
175.363	.213	.070	.063	.055	.047	.040	.153
175.936	.216	.071	.064	.056	.048	.041	.154
176.509	.219	.071	.064	.056	.048	.041	.154
177.082	.222	.072	.065	.057	.049	.042	.155
177.655	.225	.072	.065	.057	.049	.042	.155
178.228	.228	.073	.066	.058	.050	.043	.156
178.801	.231	.073	.066	.058	.050	.043	.156
179.374	.234	.074	.067	.059	.051	.044	.157
180.000	.237	.074	.067	.059	.051	.044	.157
180.626	.240	.075	.068	.060	.052	.045	.158
181.252	.243	.075	.068	.060	.052	.045	.158
181.878	.246	.076	.069	.061	.053	.046	.159
182.504	.249	.076	.069	.061	.053	.046	.159
183.130	.252	.077	.070	.062	.054	.047	.160
183.756	.255	.077	.070	.062	.054	.047	.160
184.382	.258	.078	.071	.063	.055	.048	.161
185.008	.261	.078	.071	.063	.055	.048	.161
185.634	.264	.079	.072	.064	.056	.049	.162
186.260	.267	.079	.072	.064	.056	.049	.162
186.886	.270	.080	.073	.065	.057	.050	.163
187.512	.273	.080	.073	.065	.057	.050	.163
188.138	.276	.081	.074	.066	.058	.051	.164
188.764	.279	.081	.074	.066	.058	.051	.164
189.390	.282	.082	.075	.067	.059	.052	.165
189.966	.285	.082	.075	.067	.059	.052	.165
190.592	.288	.083	.076	.068	.060	.053	.166
191.218	.291	.083	.076	.068	.060	.053	.166
191.844	.294	.084	.077	.069	.061	.054	.167
192.470	.297	.084	.077	.069	.061	.054	.167
193.096	.300	.085	.078	.070	.062	.055	.168
193.722	.303	.085	.078	.070	.062	.055	.168
194.348	.306	.086	.079	.071	.063	.056	.169
194.974	.309	.086	.079	.071	.063	.056	.169
195.600	.312	.087	.080	.072	.064	.057	.170
196.226	.315	.087	.080	.072	.064	.057	.170
196.852	.318	.088	.081	.073	.065	.058	.171
197.478	.321	.088	.081	.073	.065	.058	.171
198.104	.324	.089	.082	.074	.066	.059	.172
198.730	.327	.089	.082	.074	.066	.059	.172
199.356	.330	.090	.083	.075	.067	.060	.173
199.982	.333	.090	.083	.075	.067	.060	.173
200.608	.336	.091	.084	.076	.068	.061	.174
201.234	.339	.091	.084	.076	.068	.061	.174
201.860	.342	.092	.085	.077	.069	.062	.175
202.486	.345	.092	.085	.077	.069	.062	.175
203.112	.348	.093	.086	.078	.070	.063	.176
203.738	.351	.093	.086	.078	.070	.063	.176
204.364	.354	.094	.087	.079	.071	.064	.177
204.990	.357	.094	.087	.079	.071	.064	.177
205.616	.360	.095	.088	.080	.072	.065	.178
206.242	.363	.095	.088	.080	.072	.065	.178
206.868	.366	.096	.089	.081	.073	.066	.179
207.494	.369	.096	.089	.081	.073	.066	.179
208.120	.372	.097	.090	.082	.074	.067	.180
208.746	.375	.097	.090	.082	.074	.067	.180
209.372	.378	.098	.091	.083	.075	.068	.181
209.998	.381	.098	.091	.083	.075	.068	.181
210.624	.384	.099	.092	.084	.076	.069	.182
211.250	.387	.099	.092	.084	.076	.069	.182
211.876	.390	.100	.093	.085	.077	.070	.183
212.502	.393	.100	.093	.085	.077	.070	.183
213.128	.396	.101	.094	.086	.078	.071	.184
213.754	.399	.101	.094	.086	.078	.071	.184
214.380	.402	.102	.095	.087	.079	.072	.185
215.006	.405	.102	.095	.087	.079	.072	.185
215.632	.408	.103	.096	.088	.080	.073	.186
216.258	.411	.103	.096	.088	.080	.073	.186
216.884	.414	.104	.097	.089	.081	.074	.187
217.510	.417	.104	.097	.089	.081	.074	.187
218.136	.420	.105	.098	.090	.082	.075	.188
218.762	.423	.105	.098	.090	.082	.075	.188
219.388	.426	.106	.099	.091	.083	.076	.189
220.014	.429	.106	.099	.091	.083	.076	.189
220.640	.432	.107	.100	.092	.084	.077	.190
221.266	.435	.107	.100	.092	.084	.077	.190
221.892	.438	.108	.101	.093	.085	.078	.191
222.518	.441	.108	.101	.093	.085	.078	.191
223.144	.444	.109	.102	.094	.086	.079	.192
223.770	.447	.109	.102	.094	.086	.079	.192
224.396	.450	.110	.103	.095	.087	.080	.193
225.022	.453	.110	.103	.095	.087	.080	.193
225.648	.456	.111	.104	.096	.088	.081	.194
226.274	.459	.111	.104	.096	.088	.081	.194
226.900	.462	.112	.105	.097	.089	.082	.195
227.526	.465	.112	.105	.097	.089	.082	.195
228.152	.468	.113	.106	.098	.090	.083	.196
228.778	.471	.113	.106	.098	.090	.083	.196
229.404	.474	.114	.107	.099	.091	.084	.197
229.980	.477	.114	.107	.099	.091	.084	.197
230.606	.480	.115	.108	.100	.092	.085	.198
231.232	.483	.115	.108	.100	.092	.085	.198
231.858	.486	.116	.109	.101	.093	.086	.199
232.484	.489	.116	.109	.101	.093	.086	.199
233.110	.492	.117	.110	.102	.094	.087	.200
233.736	.495	.117	.110	.102	.094	.087	.200
234.362	.498	.118	.111	.103	.095	.088	.201
234.988	.501	.118	.111	.103	.095	.088	.201
235.614	.504	.119	.112	.104	.096	.089	.202
236.240	.507	.119	.112	.104	.096	.089	.202
236.866	.510	.120	.113	.105	.097	.090	.203
237.492	.513	.120	.113	.105	.097	.090	.203
238.118	.516	.121	.114	.106	.098	.091	.204
238.744	.519	.121	.114	.106	.098	.091	.204
239.370	.522	.122	.115	.107	.099	.092	.205
240.000	.525	.122	.115	.107	.099	.092	.205
240.626	.528	.123	.116	.108	.100	.093	.206
241.252	.531	.123	.116	.108	.100	.093	.206
241.878	.534	.124	.117	.109	.101	.094	.207
242.504	.537	.124	.117	.109	.101	.094	.207
243.130	.540	.125	.118	.110	.102	.095	.208
243.756	.543	.125	.118	.110	.102	.095	.208
244.382	.546	.126	.119	.111	.103	.096	.209
245.008	.549	.126	.119	.111	.103	.096	.209
245.634	.552	.127	.120	.112	.104	.097	.210
246.260	.555	.127	.120	.112	.104	.097	.210
246.886	.558	.128	.121	.113	.105	.098	.211
247.512	.561	.128	.121	.113	.105	.098	.211
248.138	.5						

PHI DEG	EFFICIENCY				VELOCITY RATIO		N PRIME
	MU(1)	MU(2)	MU(3)	MU(4)			
147.860	.687	.465	.300	.171	1.602		0.000
148.433	.693	.473	.308	.179	1.646		4.435
149.006	.699	.481	.316	.187	1.690		4.314
149.579	.705	.489	.324	.195	1.732		4.190
150.152	.710	.497	.333	.203	1.772		4.065
150.724	.716	.505	.341	.212	1.812		3.938
151.297	.721	.512	.350	.221	1.850		3.813
151.870	.727	.520	.359	.230	1.887		3.688
152.443	.732	.528	.368	.239	1.922		3.564
153.016	.737	.536	.377	.248	1.957		3.443
153.589	.742	.544	.386	.258	1.990		3.324
154.162	.747	.551	.395	.267	2.022		3.208
154.735	.752	.559	.404	.277	2.053		3.096
155.308	.757	.567	.413	.287	2.083		2.988
155.881	.762	.574	.422	.296	2.112		2.883
156.454	.767	.581	.431	.306	2.139		2.782
157.027	.771	.589	.440	.316	2.166		2.686
157.600	.776	.596	.449	.326	2.192		2.594
158.173	.781	.603	.458	.336	2.218		2.500
158.746	.786	.610	.467	.346	2.244		2.406
159.319	.791	.617	.476	.356	2.269		2.312
159.892	.796	.624	.485	.366	2.294		2.218
160.465	.801	.631	.494	.376	2.319		2.124
161.038	.806	.638	.503	.386	2.344		2.030
161.611	.811	.645	.512	.396	2.369		1.936
162.184	.816	.652	.521	.406	2.394		1.842
162.757	.821	.659	.530	.416	2.419		1.748
163.330	.826	.666	.539	.426	2.444		1.654
163.903	.831	.673	.548	.436	2.469		1.560
164.476	.836	.680	.557	.446	2.494		1.466
165.049	.841	.687	.566	.456	2.519		1.372
165.622	.846	.694	.575	.466	2.544		1.278
166.195	.851	.701	.584	.476	2.569		1.184
166.768	.856	.708	.593	.486	2.594		1.090
167.341	.861	.715	.602	.496	2.619		1.000
167.914	.866	.722	.611	.506	2.644		0.906
168.487	.871	.729	.620	.516	2.669		0.812
169.060	.876	.736	.629	.526	2.694		0.718
169.633	.881	.743	.638	.536	2.719		0.624
170.206	.886	.750	.647	.546	2.744		0.530
170.779	.891	.757	.656	.556	2.769		0.436
171.352	.896	.764	.665	.566	2.794		0.342
171.925	.901	.771	.674	.576	2.819		0.248
172.498	.906	.778	.683	.586	2.844		0.154
173.071	.911	.785	.692	.596	2.869		0.060
173.644	.916	.792	.701	.606	2.894		0.000
174.217	.921	.800	.710	.616	2.919		0.000
174.790	.926	.807	.719	.626	2.944		0.000
175.363	.931	.814	.728	.636	2.969		0.000
175.936	.936	.821	.737	.646	2.994		0.000
176.509	.941	.828	.746	.656	3.019		0.000
177.082	.946	.835	.755	.666	3.044		0.000
177.655	.951	.842	.764	.676	3.069		0.000
178.228	.956	.849	.773	.686	3.094		0.000
178.801	.961	.856	.782	.696	3.119		0.000
179.374	.966	.863	.791	.706	3.144		0.000
179.947	.971	.870	.800	.716	3.169		0.000
180.520	.976	.877	.809	.726	3.194		0.000
181.093	.981	.884	.818	.736	3.219		0.000
181.666	.986	.891	.827	.746	3.244		0.000
182.239	.991	.898	.836	.756	3.269		0.000
182.812	.996	.905	.845	.766	3.294		0.000
183.385	1.001	.912	.854	.776	3.319		0.000
183.958	1.006	.919	.863	.786	3.344		0.000
184.531	1.011	.926	.872	.796	3.369		0.000
185.104	1.016	.933	.881	.806	3.394		0.000
185.677	1.021	.940	.890	.816	3.419		0.000
186.250	1.026	.947	.899	.826	3.444		0.000
186.823	1.031	.954	.908	.836	3.469		0.000
187.396	1.036	.961	.917	.846	3.494		0.000
187.969	1.041	.968	.926	.856	3.519		0.000
188.542	1.046	.975	.935	.866	3.544		0.000
189.115	1.051	.982	.944	.876	3.569		0.000
189.688	1.056	.989	.953	.886	3.594		0.000
190.261	1.061	.996	.962	.896	3.619		0.000
190.834	1.066	1.003	.971	.906	3.644		0.000
191.407	1.071	1.010	.980	.916	3.669		0.000
191.980	1.076	1.017	.989	.926	3.694		0.000
192.553	1.081	1.024	.998	.936	3.719		0.000
193.126	1.086	1.031	1.007	.946	3.744		0.000
193.699	1.091	1.038	1.016	.956	3.769		0.000
194.272	1.096	1.045	1.025	.966	3.794		0.000
194.845	1.101	1.052	1.034	.976	3.819		0.000
195.418	1.106	1.059	1.043	.986	3.844		0.000
195.991	1.111	1.066	1.052	.996	3.869		0.000
196.564	1.116	1.073	1.061	1.006	3.894		0.000
197.137	1.121	1.080	1.070	1.016	3.919		0.000



APPENDIX D

COMPUTER OUTPUT FOR NOMINAL CONFIGURATION  
WITH A = .503 CM (.198 IN.)



A = .19800 B = .19200 C = .07840 R = .01425 ALPHA = 51.00 DELTA = 30.00

MU(1) = .100 MU(2) = .200 MU(3) = .300 MU(4) = .400



PRI	AI	03	AP	AW	PSIP	PSIF	CI
DEG			MU(1)	MU(2)	MU(3)	MU(4)	MU(5)
141.691	.073	.070	.065	.087	.101	.113	.123
142.126	.075	.070	.065	.080	.103	.114	.125
142.837	.077	.070	.065	.093	.107	.116	.127
143.410	.079	.070	.065	.093	.107	.118	.129
143.983	.081	.071	.065	.095	.109	.120	.130
144.556	.083	.071	.065	.097	.111	.122	.132
145.129	.085	.071	.065	.099	.113	.124	.134
145.702	.087	.071	.066	.101	.115	.126	.136
146.275	.089	.071	.066	.103	.117	.128	.138
146.848	.091	.071	.066	.105	.119	.130	.140
147.421	.093	.071	.066	.108	.121	.132	.142
147.994	.095	.071	.066	.110	.123	.134	.144
148.567	.097	.071	.066	.112	.125	.136	.146
149.139	.099	.071	.066	.114	.127	.138	.148
149.712	.101	.071	.066	.116	.129	.140	.150
150.285	.104	.072	.067	.118	.131	.142	.152
150.858	.106	.072	.067	.120	.133	.144	.154
151.431	.108	.072	.067	.122	.135	.146	.155
152.004	.110	.072	.067	.124	.137	.148	.157
152.577	.112	.072	.067	.126	.139	.150	.159
153.150	.114	.072	.068	.128	.141	.152	.161
153.723	.116	.073	.068	.130	.143	.154	.163
154.296	.118	.073	.068	.133	.145	.156	.165
154.869	.120	.073	.068	.135	.147	.158	.167
155.442	.122	.073	.068	.137	.149	.160	.169
156.015	.124	.073	.068	.139	.151	.162	.171
156.588	.126	.073	.068	.141	.153	.164	.173
157.161	.128	.073	.068	.143	.155	.166	.175
157.734	.130	.073	.068	.145	.157	.168	.177
158.307	.132	.073	.068	.147	.159	.170	.179
158.880	.134	.073	.068	.149	.161	.172	.181
159.453	.136	.073	.068	.151	.163	.174	.183
160.026	.138	.073	.068	.153	.165	.176	.185
160.599	.140	.073	.068	.155	.167	.178	.187
161.172	.142	.073	.068	.157	.169	.180	.189
161.745	.144	.073	.068	.159	.171	.182	.191
162.318	.146	.073	.068	.161	.173	.184	.193
162.891	.148	.073	.068	.163	.175	.186	.195
163.464	.150	.073	.068	.165	.177	.188	.197
164.037	.152	.073	.068	.167	.179	.190	.199
164.610	.154	.073	.068	.169	.181	.192	.201
165.183	.156	.073	.068	.171	.183	.194	.203
165.756	.158	.073	.068	.173	.185	.196	.205
166.329	.160	.073	.068	.175	.187	.198	.207
166.902	.162	.073	.068	.177	.189	.200	.209
167.475	.164	.073	.068	.179	.191	.202	.211
168.048	.166	.073	.068	.181	.193	.204	.213
168.621	.168	.073	.068	.183	.195	.206	.215
169.194	.170	.073	.068	.185	.197	.208	.217
169.767	.172	.073	.068	.187	.199	.210	.219
170.340	.174	.073	.068	.189	.201	.212	.221
170.913	.176	.073	.068	.191	.203	.214	.223
171.486	.178	.073	.068	.193	.205	.216	.225
172.059	.180	.073	.068	.195	.207	.218	.227
172.632	.182	.073	.068	.197	.209	.220	.229
173.205	.184	.073	.068	.199	.211	.222	.231
173.778	.186	.073	.068	.201	.213	.224	.233
174.351	.188	.073	.068	.203	.215	.226	.235
174.924	.190	.073	.068	.205	.217	.228	.237
175.497	.192	.073	.068	.207	.219	.230	.239
176.070	.194	.073	.068	.209	.221	.232	.241
176.643	.196	.073	.068	.211	.223	.234	.243
177.216	.198	.073	.068	.213	.225	.236	.245
177.789	.200	.073	.068	.215	.227	.238	.247
178.362	.202	.073	.068	.217	.229	.240	.249
178.935	.204	.073	.068	.219	.231	.242	.251
179.508	.206	.073	.068	.221	.233	.244	.253
180.081	.208	.073	.068	.223	.235	.246	.255
180.654	.210	.073	.068	.225	.237	.248	.257
181.227	.212	.073	.068	.227	.239	.250	.259
181.800	.214	.073	.068	.229	.241	.252	.261
182.373	.216	.073	.068	.231	.243	.254	.263
182.946	.218	.073	.068	.233	.245	.256	.265
183.519	.220	.073	.068	.235	.247	.258	.267
184.092	.222	.073	.068	.237	.249	.260	.269
184.665	.224	.073	.068	.239	.251	.262	.271
185.238	.226	.073	.068	.241	.253	.264	.273
185.811	.228	.073	.068	.243	.255	.266	.275
186.384	.230	.073	.068	.245	.257	.268	.277
186.957	.232	.073	.068	.247	.259	.270	.279
187.530	.234	.073	.068	.249	.261	.272	.281
188.103	.236	.073	.068	.251	.263	.274	.283
188.676	.238	.073	.068	.253	.265	.276	.285
189.249	.240	.073	.068	.255	.267	.278	.287
189.822	.242	.073	.068	.257	.269	.280	.289
190.395	.244	.073	.068	.259	.271	.282	.291
190.968	.246	.073	.068	.261	.273	.284	.293
191.541	.248	.073	.068	.263	.275	.286	.295
192.114	.250	.073	.068	.265	.277	.288	.297
192.687	.252	.073	.068	.267	.279	.290	.299
193.260	.254	.073	.068	.269	.281	.292	.301
193.833	.256	.073	.068	.271	.283	.294	.303
194.406	.258	.073	.068	.273	.285	.296	.305
194.979	.260	.073	.068	.275	.287	.298	.307
195.552	.262	.073	.068	.277	.289	.300	.309
196.125	.264	.073	.068	.279	.291	.302	.311
196.698	.266	.073	.068	.281	.293	.304	.313
197.271	.268	.073	.068	.283	.295	.306	.315
197.844	.270	.073	.068	.285	.297	.308	.317
198.417	.272	.073	.068	.287	.299	.310	.319
198.990	.274	.073	.068	.289	.301	.312	.321
199.563	.276	.073	.068	.291	.303	.314	.323
200.136	.278	.073	.068	.293	.305	.316	.325
200.709	.280	.073	.068	.295	.307	.318	.327
201.282	.282	.073	.068	.297	.309	.320	.329
201.855	.284	.073	.068	.299	.311	.322	.331
202.428	.286	.073	.068	.301	.313	.324	.333
203.001	.288	.073	.068	.303	.315	.326	.335
203.574	.290	.073	.068	.305	.317	.328	.337
204.147	.292	.073	.068	.307	.319	.330	.339
204.720	.294	.073	.068	.309	.321	.332	.341
205.293	.296	.073	.068	.311	.323	.334	.343
205.866	.298	.073	.068	.313	.325	.336	.345
206.439	.300	.073	.068	.315	.327	.338	.347
207.012	.302	.073	.068	.317	.329	.340	.349
207.585	.304	.073	.068	.319	.331	.342	.351
208.158	.306	.073	.068	.321	.333	.344	.353
208.731	.308	.073	.068	.323	.335	.346	.355
209.304	.310	.073	.068	.325	.337	.348	.357
209.877	.312	.073	.068	.327	.339	.350	.359
210.450	.314	.073	.068	.329	.341	.352	.361
211.023	.316	.073	.068	.331	.343	.354	.363
211.596	.318	.073	.068	.333	.345	.356	.365
212.169	.320	.073	.068	.335	.347	.358	.367
212.742	.322	.073	.068	.337	.349	.360	.369
213.315	.324	.073	.068	.339	.351	.362	.371
213.888	.326	.073	.068	.341	.353	.364	.373
214.461	.328	.073	.068	.343	.355	.366	.375
215.034	.330	.073	.068	.345	.357	.368	.377
215.607	.332	.073	.068	.347	.359	.370	.379
216.180	.334	.073	.068	.349	.361	.372	.381
216.753	.336	.073	.068	.351	.363	.374	.383
217.326	.338	.073	.068	.353	.365	.376	.385
217.899	.340	.073	.068	.355	.367	.378	.387
218.472	.342	.073	.068	.357	.369	.380	.389
219.045	.344	.073	.068	.359	.371	.382	.391
219.618	.346	.073	.068	.361	.373	.384	.393
220.191	.348	.073	.068	.363	.375	.386	.395
220.764	.350	.073	.068	.365	.377	.388	.397
221.337	.352	.073	.068	.367	.379	.390	.399
221.910	.354	.073	.068	.369	.381	.392	.401
222.483	.356	.073	.068	.371	.383	.394	.403
223.056	.358	.073	.068	.373	.385	.396	.405
223.629	.360	.073	.068	.375	.387	.398	.407
224.202	.362	.073	.068	.377	.389	.400	.409
224.775	.364	.073	.068	.379	.391	.402	.411
225.348	.366	.073	.068	.381	.393	.404	.413
225.921	.368	.073	.068	.383	.395	.406	.415
226.494	.370	.073	.068	.385	.397	.408	.417
227.067	.372	.073	.068	.387	.399	.410	.419
227.640	.374	.073	.068	.389	.401	.412	.421
228.213	.376	.073	.068	.391	.403	.414	.423
228.786	.378	.073	.068	.393	.405	.416	.425
229.359	.380	.073	.068	.395	.407	.418	.427
229.932	.382	.073	.068	.397	.409	.420	.429
230.505	.384	.073	.068	.399	.411	.422	.431
231.078	.386	.073	.068	.401	.413	.424	.433
231.651	.388	.073	.068	.403	.415	.426	.435
232.224	.390	.073	.068	.405	.417	.428	.437
232.797	.392	.073	.068	.407	.419	.430	.439
233.370	.394	.073	.068	.409	.421	.432	.441
233.943	.396	.073	.068	.411	.423	.434	.443
234.516	.398	.073	.068	.413	.425	.436	.445
235.089	.400	.073	.068	.415	.427	.438	.447
235.662	.402	.073	.068	.417	.429	.440	.449
236.235	.404	.07					

PHI DEG	EFFICIENCY			VELOCITY RATIO		N PRIME
	MU(1)	MU(2)	MU(3)	MU(4)		
141.691	.772	.611	.490	.397	1.034	0.000
142.264	.776	.616	.496	.402	1.062	2.811
142.837	.779	.621	.501	.407	1.090	2.808
143.410	.783	.625	.506	.412	1.118	2.803
143.983	.786	.630	.511	.417	1.146	2.797
144.556	.789	.634	.516	.422	1.174	2.790
145.129	.792	.639	.520	.427	1.202	2.781
145.702	.795	.643	.525	.432	1.230	2.771
146.275	.798	.647	.530	.436	1.257	2.760
146.848	.801	.652	.535	.441	1.285	2.747
147.421	.804	.656	.540	.446	1.312	2.734
147.994	.807	.660	.544	.451	1.339	2.719
148.567	.810	.664	.549	.456	1.366	2.703
149.139	.812	.668	.554	.461	1.393	2.686
149.712	.815	.672	.558	.466	1.420	2.669
150.285	.818	.676	.563	.471	1.446	2.650
150.858	.820	.680	.568	.476	1.473	2.631
151.431	.823	.684	.572	.481	1.499	2.611
152.004	.825	.688	.577	.486	1.525	2.590
152.577	.828	.692	.582	.491	1.550	2.569
153.150	.830	.696	.586	.496	1.576	2.547
153.723	.833	.699	.591	.501	1.601	2.525
154.296	.835	.703	.595	.506	1.626	2.503
154.869	.837	.707	.600	.511	1.651	2.480
155.442	.840	.710	.604	.516	1.676	2.457
156.015	.842	.714	.608	.520	1.701	2.434
156.588	.845	.717	.612	.524	1.726	2.411
157.161	.847	.720	.616	.528	1.751	2.388
157.734	.850	.723	.620	.532	1.776	2.365
158.307	.852	.726	.624	.536	1.801	2.342
158.880	.855	.729	.628	.540	1.826	2.319
159.453	.857	.732	.632	.544	1.851	2.296
160.026	.860	.735	.636	.548	1.876	2.273
160.599	.862	.738	.640	.552	1.901	2.250
161.172	.865	.741	.644	.556	1.926	2.227
161.745	.867	.744	.648	.560	1.951	2.204
162.318	.870	.747	.652	.564	1.976	2.181
162.891	.872	.750	.656	.568	2.001	2.158
163.464	.875	.753	.660	.572	2.026	2.135
164.037	.877	.756	.664	.576	2.051	2.112
164.610	.880	.759	.668	.580	2.076	2.089
165.183	.882	.762	.672	.584	2.101	2.066
165.756	.885	.765	.676	.588	2.126	2.043
166.329	.887	.768	.680	.592	2.151	2.020
166.902	.890	.771	.684	.596	2.176	1.997
167.475	.892	.774	.688	.600	2.201	1.974
168.048	.895	.777	.692	.604	2.226	1.951
168.621	.897	.780	.696	.608	2.251	1.928
169.194	.900	.783	.700	.612	2.276	1.905
169.767	.902	.786	.704	.616	2.301	1.882
170.340	.905	.789	.708	.620	2.326	1.859
170.913	.907	.792	.712	.624	2.351	1.836
171.486	.910	.795	.716	.628	2.376	1.813
172.059	.912	.798	.720	.632	2.401	1.790
172.632	.915	.801	.724	.636	2.426	1.767
173.205	.917	.804	.728	.640	2.451	1.744
173.778	.920	.807	.732	.644	2.476	1.721
174.351	.922	.810	.736	.648	2.501	1.698
174.924	.925	.813	.740	.652	2.526	1.675
175.497	.927	.816	.744	.656	2.551	1.652
176.070	.930	.819	.748	.660	2.576	1.629
176.643	.932	.822	.752	.664	2.601	1.606
177.216	.935	.825	.756	.668	2.626	1.583
177.789	.937	.828	.760	.672	2.651	1.560
178.362	.940	.831	.764	.676	2.676	1.537
178.935	.942	.834	.768	.680	2.701	1.514
179.508	.945	.837	.772	.684	2.726	1.491
180.081	.947	.840	.776	.688	2.751	1.468
180.654	.950	.843	.780	.692	2.776	1.445
181.227	.952	.846	.784	.696	2.801	1.422
181.800	.955	.849	.788	.700	2.826	1.399
182.373	.957	.852	.792	.704	2.851	1.376
182.946	.960	.855	.796	.708	2.876	1.353
183.519	.962	.858	.800	.712	2.901	1.330
184.092	.965	.861	.804	.716	2.926	1.307
184.665	.967	.864	.808	.720	2.951	1.284
185.238	.970	.867	.812	.724	2.976	1.261
185.811	.972	.870	.816	.728	3.001	1.238
186.384	.975	.873	.820	.732	3.026	1.215
186.957	.977	.876	.824	.736	3.051	1.192
187.530	.980	.879	.828	.740	3.076	1.169
188.103	.982	.882	.832	.744	3.101	1.146
188.676	.985	.885	.836	.748	3.126	1.123
189.249	.987	.888	.840	.752	3.151	1.100
189.822	.990	.891	.844	.756	3.176	1.077
190.395	.992	.894	.848	.760	3.201	1.054
190.968	.995	.897	.852	.764	3.226	1.031
191.541	.997	.900	.856	.768	3.251	1.008
192.114	.999	.903	.860	.772	3.276	0.985
192.687	1.000	.906	.864	.776	3.301	0.962
193.260	1.000	.909	.868	.780	3.326	0.939
193.833	1.000	.912	.872	.784	3.351	0.916
194.406	1.000	.915	.876	.788	3.376	0.893
194.979	1.000	.918	.880	.792	3.401	0.870
195.552	1.000	.921	.884	.796	3.426	0.847
196.125	1.000	.924	.888	.800	3.451	0.824
196.698	1.000	.927	.892	.804	3.476	0.801
197.271	1.000	.930	.896	.808	3.501	0.778
197.844	1.000	.933	.900	.812	3.526	0.755
198.417	1.000	.936	.904	.816	3.551	0.732
198.990	1.000	.939	.908	.820	3.576	0.709
199.563	1.000	.942	.912	.824	3.601	0.686
200.136	1.000	.945	.916	.828	3.626	0.663
200.709	1.000	.948	.920	.832	3.651	0.640
201.282	1.000	.951	.924	.836	3.676	0.617
201.855	1.000	.954	.928	.840	3.701	0.594
202.428	1.000	.957	.932	.844	3.726	0.571
203.001	1.000	.960	.936	.848	3.751	0.548
203.574	1.000	.963	.940	.852	3.776	0.525
204.147	1.000	.966	.944	.856	3.801	0.502
204.720	1.000	.969	.948	.860	3.826	0.479
205.293	1.000	.972	.952	.864	3.851	0.456
205.866	1.000	.975	.956	.868	3.876	0.433
206.439	1.000	.978	.960	.872	3.901	0.410
207.012	1.000	.981	.964	.876	3.926	0.387
207.585	1.000	.984	.968	.880	3.951	0.364
208.158	1.000	.987	.972	.884	3.976	0.341
208.731	1.000	.990	.976	.888	4.001	0.318
209.304	1.000	.993	.980	.892	4.026	0.295
209.877	1.000	.996	.984	.896	4.051	0.272
210.450	1.000	.999	.988	.900	4.076	0.249
211.023	1.000	1.000	.992	.904	4.101	0.226
211.596	1.000	1.000	.996	.908	4.126	0.203
212.169	1.000	1.000	.999	.912	4.151	0.180
212.742	1.000	1.000	1.000	.916	4.176	0.157
213.315	1.000	1.000	1.000	.920	4.201	0.134
213.888	1.000	1.000	1.000	.924	4.226	0.111
214.461	1.000	1.000	1.000	.928	4.251	0.088
215.034	1.000	1.000	1.000	.932	4.276	0.065
215.607	1.000	1.000	1.000	.936	4.301	0.042
216.180	1.000	1.000	1.000	.940	4.326	0.019
216.753	1.000	1.000	1.000	.944	4.351	-0.004
217.326	1.000	1.000	1.000	.948	4.376	-0.027
217.899	1.000	1.000	1.000	.952	4.401	-0.050
218.472	1.000	1.000	1.000	.956	4.426	-0.073
219.045	1.000	1.000	1.000	.960	4.451	-0.096
219.618	1.000	1.000	1.000	.964	4.476	-0.119
220.191	1.000	1.000	1.000	.968	4.501	-0.142
220.764	1.000	1.000	1.000	.972	4.526	-0.165
221.337	1.000	1.000	1.000	.976	4.551	-0.188
221.910	1.000	1.000	1.000	.980	4.576	-0.211
222.483	1.000	1.000	1.000	.984	4.601	-0.234
223.056	1.000	1.000	1.000	.988	4.626	-0.257
223.629	1.000	1.000	1.000	.992	4.651	-0.280
224.202	1.000	1.000	1.000	.996	4.676	-0.303
224.775	1.000	1.000	1.000	1.000	4.701	-0.326
225.348	1.000	1.000	1.000	1.000	4.726	-0.349
225.921	1.000	1.000	1.000	1.000	4.751	-0.372
226.494	1.000	1.000	1.000	1.000	4.776	-0.395
227.067	1.000	1.000	1.000	1.000	4.801	-0.418
227.640	1.000	1.000	1.000	1.000	4.826	-0.441
228.213	1.000	1.000	1.000	1.000	4.851	-0.464
228.786	1.000	1.000	1.000	1.000	4.876	-0.487
229.359	1.000	1.000	1.000	1.000	4.901	-0.510
229.932	1.000	1.000	1.000	1.000	4.926	-0.533
230.505	1.000	1.000	1.000	1.000	4.951	-0.556
231.078	1.000	1.000	1.000	1.000	4.976	-0.579
231.651	1.000	1.000	1.000	1.000	5.001	-0.602
232.224	1.000	1.000	1.000	1.000	5.026	-0.625
232.797	1.000	1.000	1.000	1.000	5.051	-0.648
233.370	1.000	1.000	1.000	1.000	5.076	-0.671
233.943	1.000	1.000	1.000	1.000	5.101	-0.694
234.516	1.000	1.000	1.000	1.000	5.126	-0.717
235.089	1.000	1.000	1.000	1.000	5.151	-0.740
235.662	1.000	1.000	1.000	1.000	5.176	-0.763
236.235	1.000	1.000	1.000	1.000	5.201	-0.786
236.808	1.000	1.000	1.000	1.000	5.226	-0.809
237.381	1.000	1.000	1.000	1.000	5.251	-0.832
237.954	1.000	1.000	1.000	1.000	5.276	-0.855
238.527	1.000	1.000	1.000	1.000	5.301	-0.878
239.100	1.000	1.000	1.000	1.000	5.3	



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